FULFIL: Production Control System for Managing Workflow, Quality and Flexibility in Construction

A thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

Mehrdad Arashpour

B.Sc. (Civil Eng.), M.Sc. (Cons. Eng. & Mgmt)

School of Property, Construction and Project Management

RMIT University

Melbourne, Australia

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Declaration

I certify that except where due acknowledgment has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement data of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Mehrdad Arashpour

June 2014

Abstract

Construction is an important sector of every economy. Evidence of below par performance in construction projects has been recognized by government and industry bodies. Traditional control systems with project-based approaches have not overcome endemic problems in the industry such as cost and schedule overruns and quality issues. The innovative control system proposed in this research takes a production-based approach (as opposed to a project-based approach). The FULFIL system, aims to stabilise the workflow, minimise interruptions caused by quality problems and maximise the flexibility in process design. The FULFIL system of production control is based on four pillars: queuing theory, transformation/flow/value theory, factory physics, and theory of constraints. In order to propose the principles of the FULFIL system, analytical and simulation models of construction production are developed. In the constructed models, different production scenarios are compared and contrasted and tangible performance measures of the production are measured.

This thesis is driven by seven research objectives: 1) To analyse the impact of workflow variability on construction production. The results of the current research confirm that performance in construction is adversely affected by workflow variability caused by factors such as rework and capacity imbalance. Furthermore, the work shows it is possible for specialty contractors, who have the direct responsibility for production management, to effectively offset the impacts of variability by using FULFIL protocols to control activity starts.

2) To establish a tailored modelling approach that precisely quantifies variability in the flow of work amongst specialty contractors. This thesis proposes a new modelling approach using a relative indicator of variability. This approach takes both the standard deviation of time between completions and the average processing time into consideration. It innovatively determines the start rate of a given contractor's activity using the variability indicator of the predecessors in the production network.

3) To explore approaches to stabilising the workflow in construction production. Two principles for stabilising the workflow are proposed and tested. Limiting the number of jobs under construction and integrating work processes are confirmed to be effective in prevention of frequent work starvations and overloads in the production network.

4) To explore opportunities for variability reduction in construction production. Tangible performance measures in production networks using due date driven and rate driven strategies are analysed. FULFIL analysis shows that when new construction is authorised, not scheduled, the production system is more efficient, controllable and robust against control errors.

5) To explore opportunities for variability buffering in construction production. The results show that there should be a mechanism to buffer against the remaining variability after applying variability reduction tools and strategies. The user-friendly framework for defining optimum-sized capacity buffers in the FULFIL system is developed and tested. The framework realises the trade-offs between oversized buffers resulting in lost revenue and undersized buffers resulting the risk of late completions.

6) To explore opportunities for improving the flexibility in construction processes. Two sources of inflexibility in process designs are analysed and addressed. Depending on the level of capacity imbalance and processing time variability, different cross-training strategies are proposed and tested. When processing times are variable, capacity should be shifted in an indirect path to the bottlenecks.

7) To explore opportunities for reducing interruptions caused by quality problems and rework. Three variables of rework are analysed and strategies to address them are proposed. Rework duration and intervals, and the timeframe of call-backs are shown to have significant impacts on the performance of construction and can be effectively offset by using FULFIL protocols to control interruptions caused by rework.

This thesis contributes to the body of knowledge by developing a deeper insight into the dynamics of workflow, quality and flexibility management, and the resulting impacts on construction plan reliability. Furthermore it can assist industry practitioners in finding the most cost-effective way to operate and control production networks. Easy-to-use models developed and tested in this thesis can improve the traditional project-based controls in construction. Opportunities for future research have been identified at the end of each chapter and also in the concluding chapter.

Acknowledgements

The completion of this thesis is a result of much sacrifice and dedication on the part of my family members. This research could not have been delivered without this much appreciated support.

First of all, praise belongs to my God for all of my many blessings. I owe all that I am and all that I have achieved to Allah who loves and watches over me day and night.

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Special thanks go to academics and higher degree by research students at the School of Property, Construction and Project Management in RMIT University. I am grateful to Associate Professors Tayyab Maqsood, Guillermo Aranda-Mena and Professor Kerry London for their teachings and encouragement. I would also like to thank Dr. Ehsan Gharaie, Dr. Wejendra Reddy, Professor Sujeeva Setunge, and Dr. Babak Abbasi for their constructive comments and recommendations about my research. Thanks also go to Associate Professor Eric Lee in the City University of Hong Kong for his continuous support.

Finally, I would like to express my gratitude to the Royal Melbourne Institute of Technology that provided the financial support for this research. I would also like to thank the RMIT School of Graduate Research for providing me the prestigious HDRPG Research Grant. Thanks also go to all others who supported me directly and indirectly in the data collection process, especially Mr Anthony Pohlner in Monarch Building systems, Mr Graeme Black in Lignor Ltd, and Mr George Gelberidis in Hickory Construction Group.

To Mahdi,

Who will eventually rise up and unite mankind

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1. Chapter One – Introduction

"Time waste differs from material waste in that there can be no salvage. The easiest of all wastes, and the hardest to correct, is this waste of time, because wasted time does not litter the floor like wasted material". Henry Ford (1863- 1947)

1.1. Conceptual framework

Operational performance in construction production systems is assessed based on measures such as completion time, cost, quality and service level. Production systems, however, are prone to non-uniformity and interruptions caused by a wide range of variables. External variability is mainly caused by factors outside the project environment such as extreme weather conditions (Loosemore, Chow et al. 2012) and non-stationary market demand (Barriga, Jeong et al. 2005, Vidalakis, Tookey et al. 2013). Internal variability can result from different sources such as unstable workflows (Palaniappan, Sawhney et al. 2007, Halpin 2010), workforce motivation (Han, Park et al. 2008, Arashpour, Shabanikia et al. 2012), and quality/rework issues (Sawhney, Walsh et al. 2009, Love, Edwards et al. 2010). Variability results in time and budget overruns, which are endemic problems in construction projects (Ballard 2012).

In order to address the high level of variability in projects and transfer the resulting risks, the construction industry heavily relies on subcontracting. However, managing the hand-offs (workflow) in interconnected network of trade contractors is a difficult task. Traditional approaches in construction project management assign each process to a trade contractor with an individual specialisation, and trades with the greatest work content (bottlenecks) have great influence on the progress rate of the project.

Attempts have been made in order to improve traditional methods of construction project management. For example, resource driven scheduling or Critical Chain Project Management (CCPM), which is based on the theory of constraints (Goldratt and Cox 2005), adds more accuracy to the Critical Path Method (Del la Garza and Kyunghwan 2009). Furthermore, lean construction (Ballard and Howell 1994, Sacks, Treckmann et al. 2009) and even flow production (Bashford, Sawhney et al. 2003) are being increasingly cited in the construction management literature as means of optimizing performance measures such as lead time, profit, output/throughput (TH), and service level.

In the construction engineering and management literature, effects of variability on production have been investigated. However, holistic research on the on-site operational aspects of the construction process is sparse (Winch 2006, Turner, Ledwith et al. 2010, Anumba and Wang 2012). This limitation and the need to optimize the performance and productivity in construction production motivate research in process design and workflow analysis and explain the rationale behind the present research.

This thesis proposes a control system, the FULFIL system, that addresses critical issues in construction production including workflow variability – analysis of the impacts of workflow variability on performance; modelling variability in the flow of work amongst specialty contractors; stabilising the workflow in the production network; variability reduction; variability buffering; maximising process flexibility; and minimising the interruptions caused by quality problems. In general, the FULFIL system of production control improves traditional control techniques that solely focus on after-the-fact detection of variances. It was found to significantly affect the speed at which the construction processes were completed and have a significant impact on reducing the workflow variability and management effort.

The FULFIL system of production control has been founded on four theoretical pillars that is illustrated in Figure 1.1.

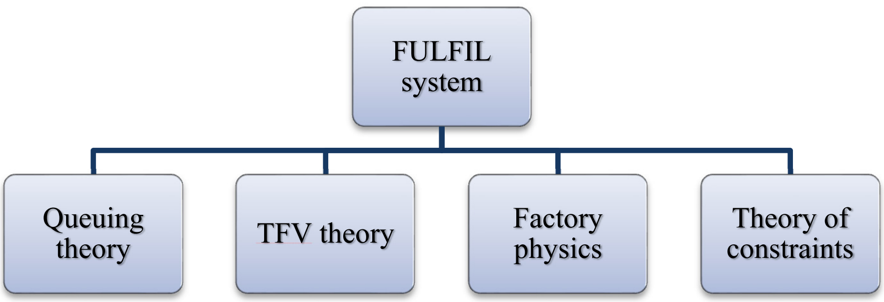


Figure 1.1. Theoretical basis of the research

This research is theoretically based on four pillars:

- Queuing theory has been adopted from well-founded discipline of mathematics in order to construct robust analytical models of construction production networks.

- TFV theory that is based on transformation-flow-value generation model of production (Koskela 2000),
- Factory Physics principles that built a framework for production management (Hopp & Spearman 2008),
- Theory of constraints proposed by (Goldratt, Cox et al. 1992) and its project-specific application of critical chain project management (CCPM).

1.2. Research aim and objectives

The aim of this research is to improve performance in construction production by designing and testing a production control system that stabilises the workflow, minimises interruptions caused by quality problems, and maximising flexibility in process design. Figure 1.2 illustrates the aim graphically.

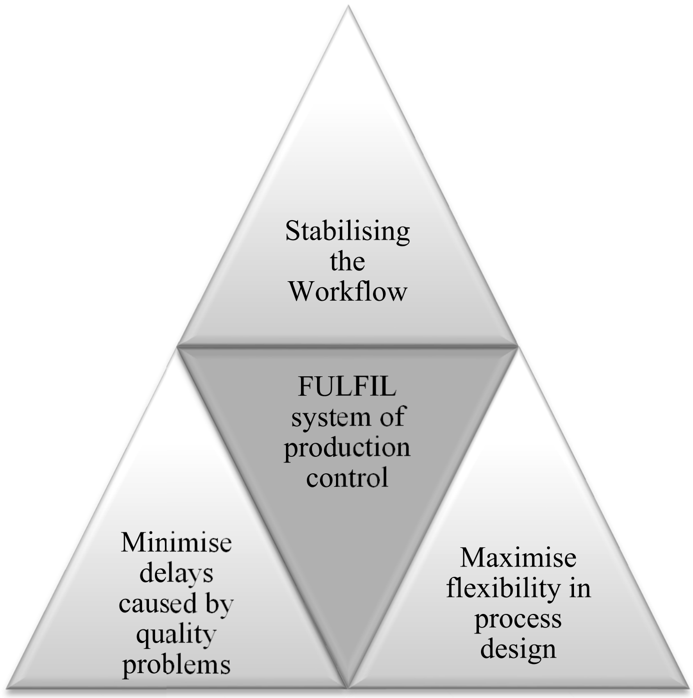


Figure 1.2. The FULFIL system of production control

The aim was translated into seven research objectives:

1. To analyse impacts of workflow variability on construction production

2. To establish a tailored modelling approach that precisely quantifies variability in the flow of work (handoffs) amongst specialty contractors

3. To explore approaches to stabilising the workflow in construction production

4. To explore opportunities for variability reduction in construction production

5. To explore opportunities for variability buffering in construction production

6. To explore flexibility improvement opportunities through cross-training resources

7. To explore opportunities for reducing interruptions caused by quality problems and rework.

These objectives are investigated and addressed throughout the thesis.

1.3. Research design

This research aims to follow scientific rules for a systematic quantitative research. Three elements of design framework for this research include: worldview and epistemology, strategy of inquiry, and research methods.

- Philosophical worldview: Post-positivism challenges the traditional worldview of the absolute truth of knowledge and refers to the thinking after positivism. The major elements of this position include determination, reductionism, empirical observation and measurement, and theory verification (Creswell 2009). Objectivist epistemology and realist ontology identify this research.

- Strategy of inquiry: Quantitative strategy of inquiry is the main approach to empirical work in this thesis. An overview of different quantitative methodologies has been presented in Table 1.1.

Table 1.1. Review of different quantitative strategies of inquiry

Research methodology	Methodology overview
Experimental research	Seeks the influence of a specific treatment on an outcome. In conducting experiments, the treatment is provided to one group and withheld from another to compare the outcomes.
Quantitative case study	Explore an activity or process in depth. Quantitative data from cases are collected using different approaches such as archival analysis, observation and historical analysis.
Analytical Modelling	Characterises a situation in the real world by building logical parametric models. Mathematical techniques are used to analyse the models and yield solutions.
Scenario analysis	Analyses possible alternative paths of a real-world environment and attempts to improve the process of decision making by considering possible outcomes (alternative future).
Simulation	Represents processes and mimics behaviour in complex real-world systems. Common discipline's techniques are used analyse simulation models and yield numerical values.

The quantitative model of this project aims to provide specific directions for research design procedures. The quantitative case study is the best approach for the current research considering the aim, objectives and availability of data. Multiple case studies in this project were investigated including different construction companies in Queensland and Victoria, Australia. The application of a mixed methodology, in which both analytical and simulation modelling are conducted to analyse the data collected from case studies, provides a robust research approach in the field of construction engineering and management (Fellows and Liu 2008).

- In order to propose the principles of the FULFIL system, processes of construction production are first modelled analytically using the queuing theory. In the constructed models, different production scenarios are compared and contrasted and tangible performance measures of the production are measured. In the next step, processes of construction production are simulated. This step allows relaxing the assumptions behind constructing the analytical models and analysing many different what-if scenarios in real-life construction. More than 5000 simulation experiments enable the current research to identify most effective interventions in order to improve the performance in construction production systems. Furthermore, comparing results of analytical and simulation models provide a measure of validation for results. Figure 1.3 illustrates different steps for data collection and analysis in this research.

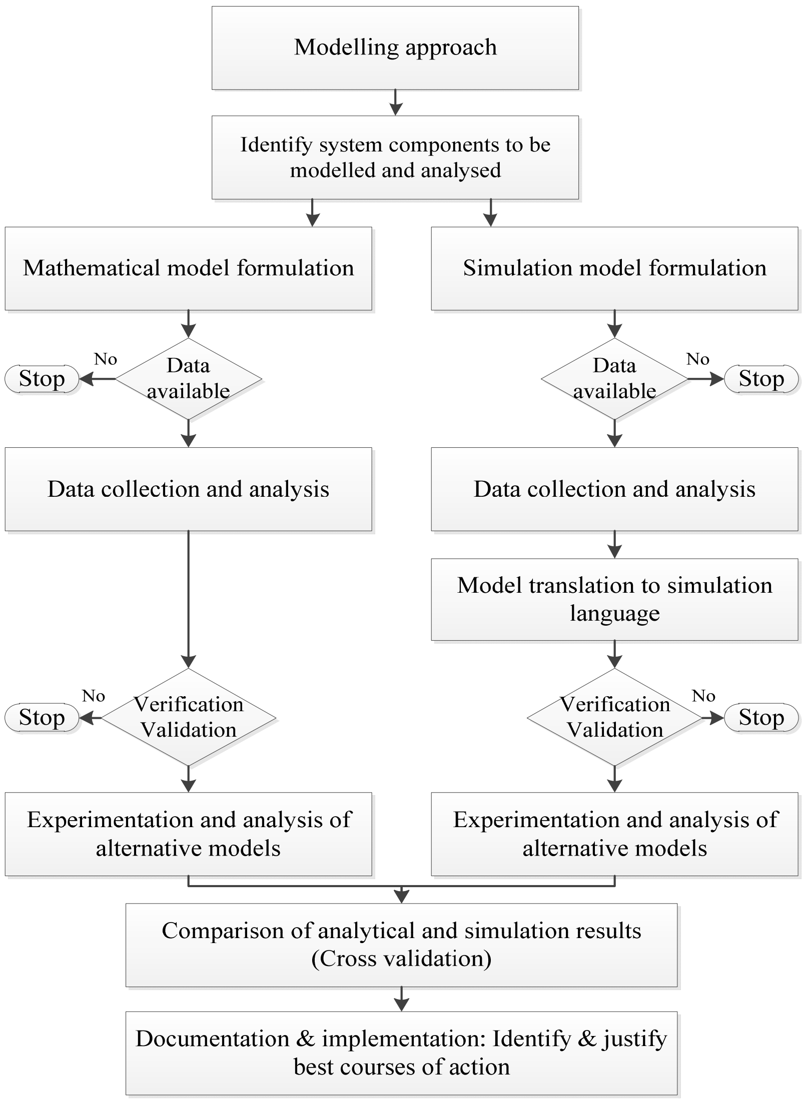


Figure 1.3. Graphical illustration of the research steps

1.4. Rationale for the choice of case studies and Validity of results

The case studies (companies) involved in this investigation are national in scope, operating in markets across Australia as well as Melbourne and Brisbane. They all have the production capacity of building 500+ residential units per year. The understanding gained by the researcher is that residential construction characteristics in Australia from a production point of view are similar to those in the chosen case studies.

The process of validation ensures that the model behaves the same as the real-world system (Fellows and Liu 2008). The following steps were adopted in order to validate the thesis results:

- Step 1- Case study participants were briefed about the methodology used to develop the models and the way production data were utilised. Agreement of stakeholders upon all modelling assumptions resulted in development of models with high face validity.
- Step 2- On-going production processes of the two case studies were modelled and run 100 times. Throughput rates and cycle times were checked against the collected data. The simulation results and real-world production data were almost identical, with errors within the range of 0.2%.
- Step 3- Well-founded analytical approaches such as queuing theory and Little's law (Little 1961) were used to compute the production parameters, which were found to be consistent with those of the constructed models.
- Step 4- Sensitivity analysis on results that was conducted by slight manipulation of the model input variables found no extreme variations in the results.

With the completion of these steps, the system was considered as validated and reasonably robust.

1.5. Research contributions

This research makes the following contributions to the body of knowledge:

- The FULFIL system of production control, which is based on queuing theory, TFV theory, factory physics, and theory of constraints, improves the traditional concept of project control. This research takes a holistic approach and analysis in order to stabilise workflow, minimise delays and maximise flexibility.
- This thesis develops a deeper insight into the dynamics of workflow, quality and flexibility, and the impacts on construction plan reliability.
- The current research contributes to the production control theory by:
    - Identifying the superior production control protocols in construction production
    - Optimising the size of capacity buffers in order to improve workflow stability
    - Minimising the delays, especially those caused by quality problems
    - Maximising process design flexibility in construction production

1.6. Structure of the thesis

Modelling paradigms in the construction literature for addressing production problems are reviewed in chapter two. Chapter three presents the first element of the FULFIL analysis in order to quantify impacts of workflow variability on performance in construction production. Chapter four proposes a new approach for modelling workflow variability in construction production networks. Chapters five, six and seven are dedicated to variability management in the FULFIL system. Chapters eight and nine describe strategies to maximise process flexibility and minimise quality-related delays respectively. A summary of findings with regard to research objectives are presented in chapter 10 followed by appendices. Figure 1.3 illustrates the layout of thesis chapters.

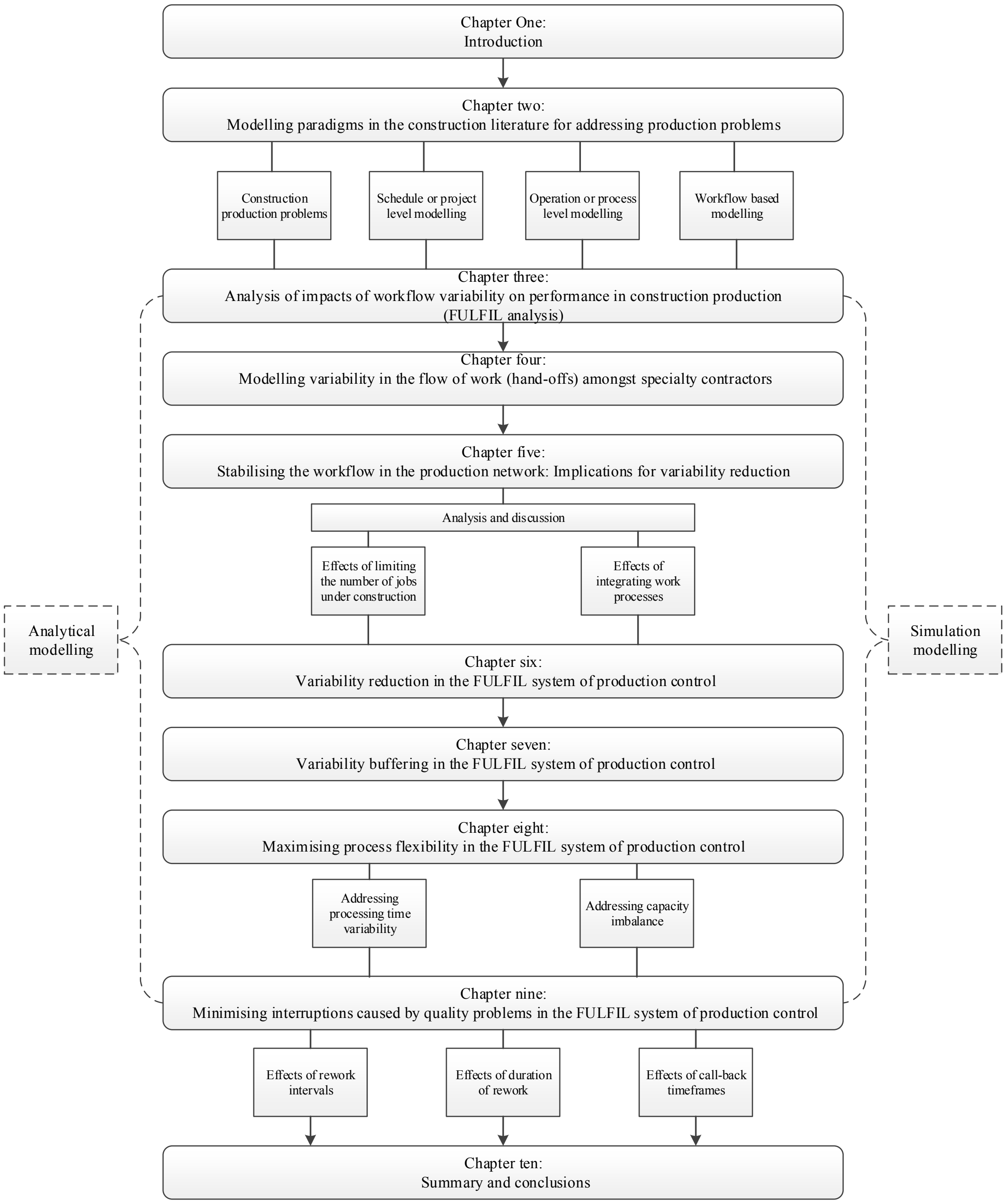


Figure 1.4. Structure of the thesis

1.7. Publications

1.7.1. Journal articles published

Arashpour, M., R. Wakefield, N. Blismas and E. W. M. Lee (2014). "A framework for improving workflow stability: Deployment of optimized capacity buffers in a synchronised construction production." *Canadian Journal of Civil Engineering*. DOI: 10.1139/cjce-2014-0199.

Arashpour, M., R. Wakefield, N. Blismas and E. W. M. Lee (2014). "Analysis of disruptions caused by construction field rework on productivity in residential projects", *Journal of Construction Engineering and Management* 140 (2)

Arashpour, M., R. Wakefield, N. Blismas and E. W. M. Lee (2013). "A new *approach* for modelling variability in residential construction projects"*, Australasian Journal of Construction Economics and Building,* vol. 13, no. 2, pp. 83-92

1.7.2. Journal articles under review

Arashpour, M., R. Wakefield, N. Blismas, J. Minas. "Optimization of process integration and multi-skilled resource utilization in off-site construction" *Journal of Automation in Construction.*

Arashpour, M., R. Wakefield, N. Blismas, Y. Maqsood. "Automation of Production Tracking for Augmenting Output in Off-site Construction" *Journal of Automation in Construction*.

Arashpour, M., R. Wakefield, N. Blismas, B. Abbasi. "Analysis of performance in rate-driven construction: Issues of efficiency, supervision and controllability" *Journal of Construction Engineering and Management.*

1.7.3. Peer reviewed conference papers

"Improving construction productivity: implications of even flow production principles", *CIB World Building Congress 2013: Construction and Society*, Queensland University of Technology.

"Role of simulation in construction processes- Harmony in capturing resources". DOI: 10.3850/978-981-08-7920-4', paper presented to *Research, Development, and Practice in Structural Engineering and Construction 2012*, Curtin University, Perth.

Arashpour, M., & Arashpour, M. (2012). A collaborative perspective in green construction risk management. Paper presented at the *37th Annual Conference of Australasian Universities Building Educators Association (AUBEA),* University of New South Wales, Australia.

1.8. Notations, symbols and terminology

In different chapters of this thesis, these notations, symbols and terminology have been used:

CONWIP	Constant Work-In-Process
CSC	Closed Skill Chains
CT	Cycle Time
DES	Discrete Event Simulation
DCB	Direct Capacity Balancing
DOR	Duration of Rework
E (.)	Expected value of

f (.)	Function of
FCT	Full Cross-Training
FIFO	First-In-First-Out
<u>FULFIL</u>	work<u>F</u>low, q<u>U</u>a<u>L</u>ity, and <u>F</u>lexib<u>IL</u>ity management
GLM	General Linear Model
HCT	Hybrid Cross-Training
P (.)	Probability of
PAR	Performance Ability Ratio
PSC	Partial Skill Chaining
RI	Rework interval
TH	Throughput rate
U	Utilisation level
VI	Variability Index
WIP	Work-In-Process (inventory)
w_0	Critical level of work-in-process
r_b	Processing rate of bottleneck
r_e	Effective processing rate

TPS Toyota Production System

t_a Arrival time (average time between start of activities)

t_e Effective processing time

$\hat{x}_t$ Forecast variable at time t

σ^2 Variance

μ Mean

$\Phi(.)$ Cumulative distribution function

* Optimum form

2. Chapter Two – Modelling paradigms in the construction literature for addressing production problems

2.1. Introduction

In this chapter of the thesis, workflow modelling strategies in the mainstream literature are reviewed. To complement the contents of this brief chapter, a more detailed treatment of the relevant literature has been incorporated to the beginning of each chapter.

2.2.Construction production problems

Construction production systems face several problems that directly affect their tangible performance measures. These problems include but are not limited to: long cycle times (Bashford, Walsh et al. 2003), insufficient use of resources (Sacks, Koskela et al. 2010), excessive number of jobs under construction (Love, Holt et al. 2002), lost throughput rate (AbouRizk, Knowles et al. 2001), interruptions and delays (Damrianant and Wakefield 2000), and inflexible production processes (Walker and Shen 2002, Hajdasz 2014).

To address these issues several modelling initiatives have been developed in the construction literature that can be categorized into three main groups. These models can facilitate the processes of planning, monitoring and controlling of construction projects. Figure 2.1, illustrates a map of the construction management literature with regard to production problems and the modelling efforts to address them.

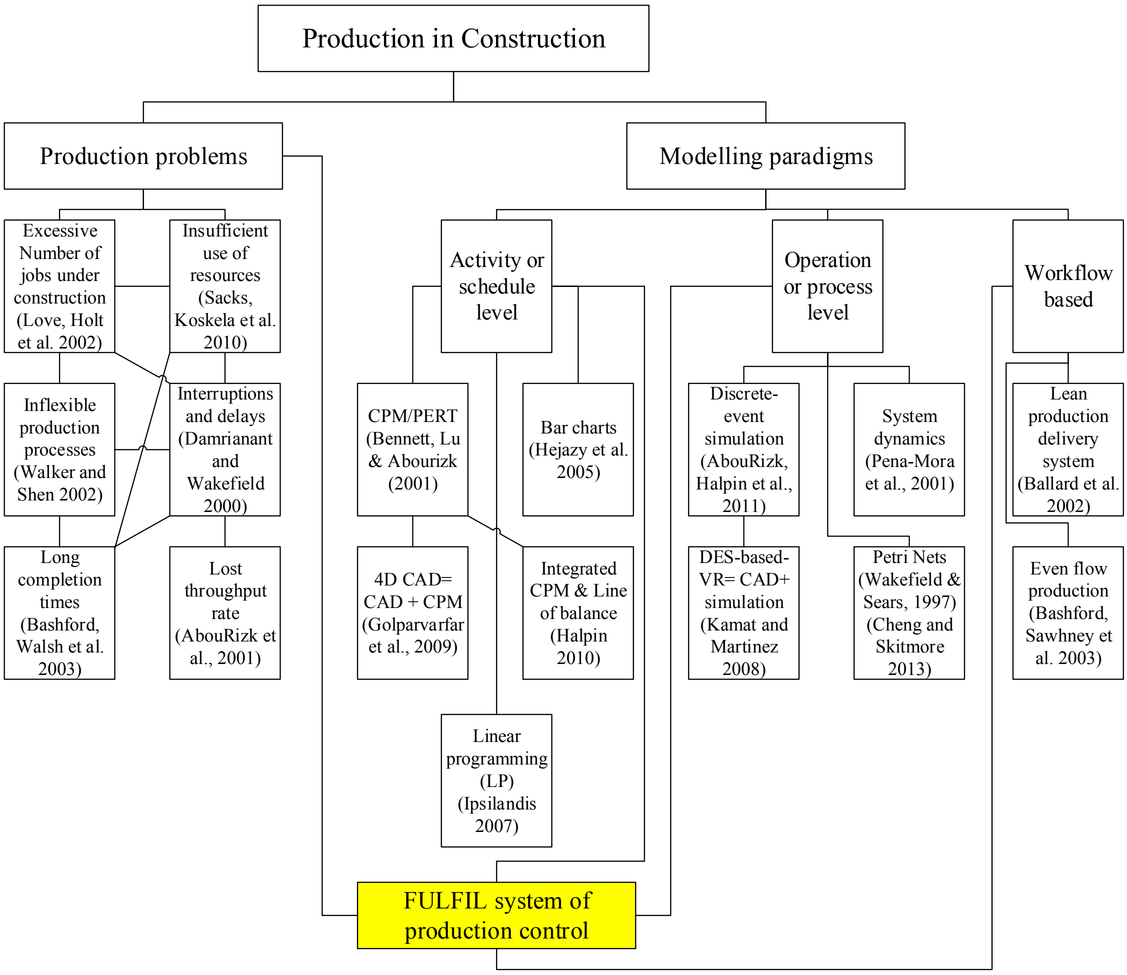


Figure 2.1. A map of literature- production problems and relevant modelling efforts

2.3. Schedule or project level modelling

The aim of this modelling approach is to analyse discretely evolving construction products and describe what is built where and when. These models study spatial and temporal interferences and optimal activity sequence (Kamat, Martinez et al. 2011). Activity level visualisation combines activity-based construction schedules, such as critical path method (CPM) or bar charts, and 3D computer-aided design (CAD) models of facilities in order to create four-dimensional visualisation (4D-CAD).

The state-of-the-art practice is to use four dimensional models in the augmented reality (4D AR) in order to integrate as planned (expected) and as built (actual) visualizations. This enables managers to monitor and control construction performance using building information models

(BIM). In this way, as-planned and as-built performances are compared in order to show what is expected to be built where and when, and the interactions among personnel, equipment and material are analysed. In this level of planning, BIM, which is typically used at design and preconstruction stages, is extended to the construction phase to compare and contrast as-planned and as-built performances. This facilitates remote construction control decision making and also reduces the wasted time in contractor coordination.

2.4. Operation or process level modelling

At the process level, simulation modelling represents a framework to design, analyse and improve construction operations. Dynamic operation level planning is rooted in discrete event simulation (DES) and combines operation planning tools (i.e. simulation models) and CAD models of static and dynamic entities. Here, the focus is to analyse interaction between resources, machines and materials in order to communicate not only what, where and when of the construction product but also who builds it and how. It depicts the continuous evolvement of products and processes (Kamat, Martinez et al. 2011).

Designing construction processes is about comparing alternative construction methods, equipment, labour assignments, temporary structures, and operating strategies to undertake the planned operations. By visualization of simulation models, project participants can graphically see (on the computer) the processes that would be done in the real site by conducting virtual walkthroughs (Ganah, Bouchlaghem et al. 2005). Discrete event simulation and virtual reality can be combined to form what is called DES-based-VR. In the virtual reality environment, the logic of DES model can be validated and decision makers can provide feedback on the model.

Discrete-event simulation systems are characterized by their application breadth (general purpose or special purpose), flexibility (being programmable), and simulation paradigm, which can be either Process Interaction (PI) or Activity Scanning (AS). AS-based discrete-event simulation take the advantage of Activity Cycle Diagrams (ACD), to simulate complex construction operations (Martinez and Ioannou 1999). The logic behind this paradigm is that in manufacturing systems, materials arrive and undergo a fixed processing pattern; however, construction operations capture many interacting resources.

Construction operations can also be precisely modelled by means of other graphical and mathematical models. For example Damrianant and Wakefield (2000) used Petri nets to simulate and model construction systems. In this way, the model is flexible as it integrates both simulation-modelling constructs and well-founded analytical models (Arashpour, Wakefield et al. 2013).

2.5. Workflow based modelling

Based on the flow conceptualisation, production is not a single-stage process of transforming input to output. Other stages such as transportation, delays and inspections are also included in the production (Koskela 2000). Flow variability in production systems can be the result of management decisions or randomness in process and demand (Hopp and Spearman 2008). Subcontracting the construction processes to a large number of trade contractors can make the management of job movements (hand-offs) difficult.

Effects of workflow variability on project performance have been investigated in the construction management (CM) literature. For instance, Arashpour and Arashpour (2011) and Liu, Ballard et al. (2011) showed how labour productivity is directly correlated with different measures of workflow variability. Other applications of workflow planning have been used to develop lean construction models. The Last Planner system of production control (Ballard 2000) is the masterpiece in this research area.

2.6. Evolution of tools for modelling the workflow in construction

Production cycle time is usually regarded as one of the main performance measures in projects (Hopp and Spearman 2008). Attempts have been made to optimise both pre-construction and construction phases in order to shorten completion times. Whereas improvements in both phases have been considerable, the construction industry is still regarded as fragmented, with much room for improvement (Ballard and Koskela 2009).

Traditional project planning uses Critical Path Method (CPM) as its main tool. However, there is a degree of scepticism about the capability of CPM to manage interconnected construction processes (Tommelein, Riley et al. 1999). In fact, traditional project management tools such as CPM scheduling, earned value analysis and cost estimating fall short when representing interlinked processes and the frequent seize and release of required resources that happens in construction (Bashford, Walsh et al. 2003).

To address these issues, a production planning worldview in construction, which is inspired by manufacturing, focuses on not only individual activities but also interlinked resources. This school of thought in construction management has emerged based on the theory of hierarchical construction operations (Halpin and Woodhead 1976). Production management uses Discrete Event Simulation (DES) for modelling and scheduling. The historical development of construction simulation languages is presented in the following.

There are many variables in a construction project that make the models very complex. Simulation modelling is a useful tool to analyse those construction models that cannot be solved analytically. Simulation is capable of providing information about system behaviour under different what-if conditions (AbouRizk, Halpin et al. 2011). Construction simulation tools have been widely developed and used in order to model production processes. Figure 2.2 shows the evolutionary trend of both general purpose and domain-specific tools in construction simulation.

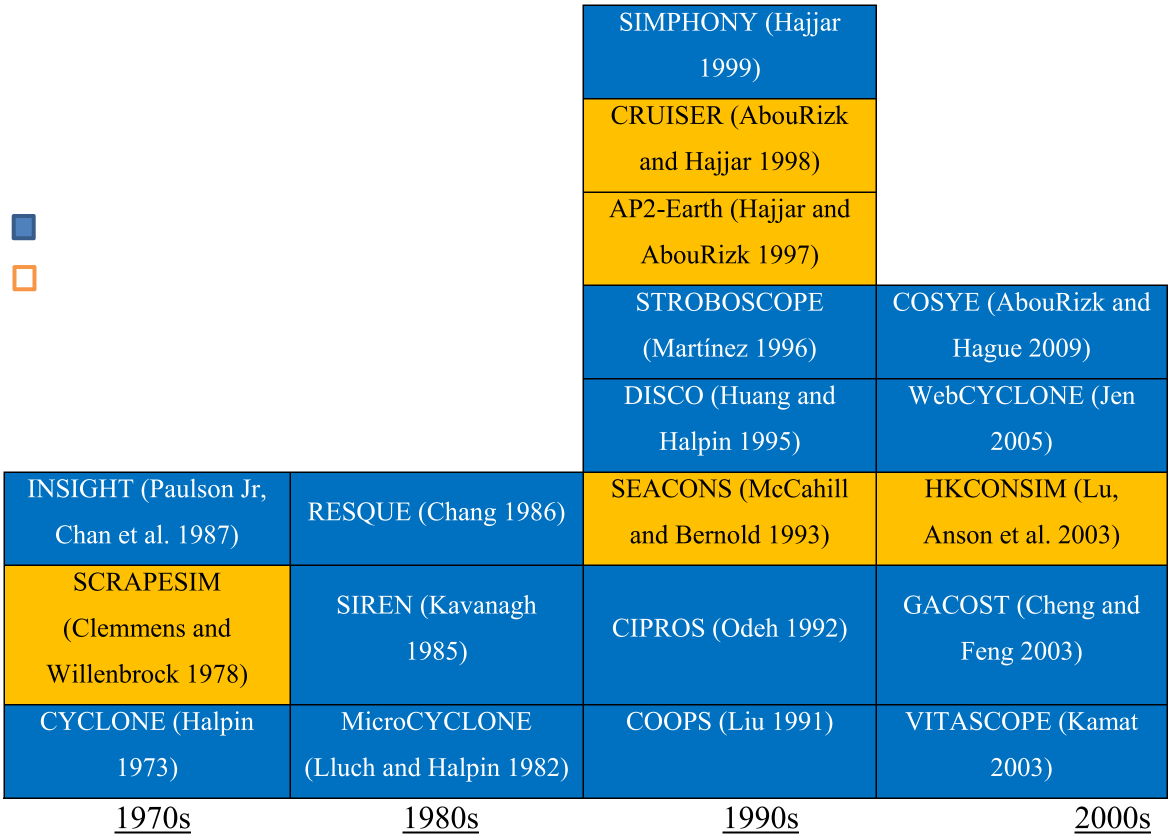


Figure 2.2. Historical evolution of construction simulation tools

These construction simulation languages have been used to model construction processes and relative parameters such as completion time and work-in-process inventory (Naresh and Jahren 1995, Kamat and Martinez 2008, González, Alarcón et al. 2009, Behzadan and Kamat 2011). Although DES can model workflow in general production settings, improvements are required to distinguish the unique characteristics of workflow in construction (Akhavian and Behzadan 2011). Furthermore, the literature is sparse concerning holistic models for construction systems that involve consideration of production control related problems.

In order to bridge these gaps, a tailored production control system for construction is proposed and tested in this research. FULFIL system adopts a holistic approach towards addressing construction production problems and aims to stabilise the workflow, minimise quality problems and maximise flexibility in construction processes.

3. Chapter Three – Analysis of impacts of workflow variability on performance in construction production (FULFIL analysis)

3.1. Introduction

Chapter two investigated different modelling paradigms in the construction production. The models perceive the workflow variability as the root cause for most, if not all, production problems. This chapter aims to meet the first research objective and analyse impacts of workflow variability on productivity and performance in construction. Findings of chapter three about the first objective form the basis of FULFIL propositions to control workflow variability in chapters four to seven. The first objective of the thesis is to investigate the effects of work flow variability on construction productivity. Variation in worksites is caused by many factors such as variable intervals between activity starts and also rework. The investigations in this chapter on the first objective reveal that variation can significantly inflate completion times and result in workflow congestions and wasted time in the interconnected network of trades.

House building is an important sector of the construction industry. Evidence of a shortage in supplying new housing has been recognized by government and industry bodies. The National Housing Supply Council (NHSC) and Housing Industry Association (HIA) estimate a shortage of half a million houses in Australia by 2020. Contributing to the growing shortage of house supply is the issue of long completion times. Traditional control systems with project-based approaches have not overcome endemic problems in the industry such as cost and schedule overruns and quality issues.

The meeting of milestones presents a constant challenge in construction projects. One root cause behind this challenge is the presence of variability in the project workflow. In fact, impacts of variability at both trade-contractor level and project level remain difficult to manage. Construction worksites are dynamic environments and subject to a high level of variability. External variability is mainly caused by factors outside the project environment such as extreme weather conditions (El-Adaway 2012) and non-stationary market demand (Ahmad 1999, Barriga, Jeong et al. 2005). Internal variability can result from different sources such as unstable workflows (Laufer, Woodward et al. 1999, Palaniappan, Sawhney et al. 2007), workforce motivation (Han, Park et al. 2008, Arashpour, Shabanikia et al. 2012), and quality issues causing rework (Josephson, Larsson et al. 2002, Love and Smith 2003).

In the presence of variability, it is not always possible to increase the rate of starting new constructions by accelerating the bottleneck processes. Research in the international level has shown that increasing the availability of construction resources and levels of employment in the industry have not improved the productivity significantly (Mawhinney 2008, Mubarak 2010). Furthermore, it is often not possible to increase the availability of labour resources (trade contractors) as there are strong barriers of entry into some trades. For example, a plumber or electrician needs to work as an apprentice for several years before becoming a licensed tradesman. These limitations and the need to optimize the performance and productivity in the residential construction motivate research in process design and workflow analysis and explain the rationale behind the present study.

In the construction engineering and management literature, effects of variability on production have been investigated (Shoura and Singh 1997, Liu, Ballard et al. 2011). However, holistic research that considers impacts of workflow variability on productivity and performance at both project and trade contractor levels is sparse (Yung and Yip 2010, Yu 2011).

3.2. Research methodology

The purpose of this chapter is to analyse the effects of workflow variability on tangible performance measures of construction projects. Production data of two residential builders were collected. At the first stage, single trade contractor processes were analytically modelled in order to analyse the performance metrics at this level. Performance metrics for the plumbing trade were measured and analysed using the principles of the queuing theory.

At the second stage of the research, the entire project network was modelled using discrete event simulation (DES) in order to keep track of tangible performance metrics at the project level. Care was taken in order to build accurate models that reflect complex interactions in construction sites and workflow within the interlinked network of trade contractors. In reality, trade contractors are not operating independently and the completed work of a given trade is required for a successor trade to proceed. Simulation experiments were designed in order to analyse real-life what-if production scenarios, each with different levels of workflow variability.

The application of a mixed methodology, in which both mathematical and simulation modelling are conducted, provides a robust research approach in the field of construction engineering and management (AbouRizk and Hague 2009, Lee, Fung et al. 2013). Simulation has been used as a decision support tool in the construction engineering literature (Back and Bell 1995, Anumba and Aziz 2006, Min and Bjornsson 2008). Furthermore, comparative analysis of simulation and of mathematical models provides a measure of validation and test the accuracy of the developed models (Wang 2004, Castro-Lacouture, Süer et al. 2009).

3.3. Impacts of workflow variability on the productivity at the trade level

Data obtained in previous studies show that variability in construction processes degrades the performance measures of trade contractors (Tommelein, Riley et al. 1999, Arashpour, Wakefield et al. 2013). When variability is present, construction process times are no longer deterministic. Furthermore, variable processes decrease the capacity of the production network and inflate the construction duration (Doloi, Iyer et al. 2011). Rework or re-entrant flow is an important cause of variability in construction projects that causes processes to be unpredictable (Brodetskaia, Sacks et al. 2013). In construction projects, rework can be caused by construction faults discovered through formal/compulsory stage inspections or informal worksite observations. Another type of rework is client-related rework, which is caused by changes in project scope, plan and design by the client (Hwang, Zhao et al. 2013). Production data of two residential builders were collected in order to analyze the impacts of workflow variability on production and performance. Details of construction processes in the worksites were captured during numerous site visits. Snapshots of the two worksites are shown in Figures 3.1 and 3.2.

Figure 3.1. Construction worksite (case study #1)

Figure 3.2. Construction worksite (case study #2)

Rework data including the number of instances and durations were collected. The long-term probability of having a quality issue, which results in rework, is different for trades. When a construction process is subject to rework, trade contractors have to return to the same place multiple times. For example, the plumbing trade had to come back to the worksite for 10 times in order to rectify the faults (for a total of 40 jobs completed in different apartments). In this way, the probability of rework for the plumbing trade was P=25%. Based on the site observations, the plumbing trade needed an average of $t_0 = 3$ days to complete the job in an apartment. Figure 3.3 shows a schematic illustration of rework loop in the plumbing process within the interconnected trade network.

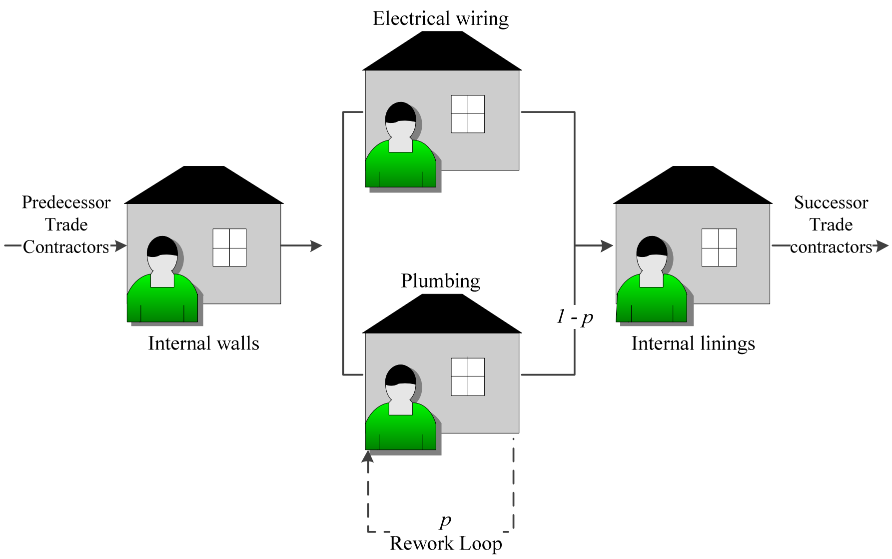


Figure 3.3. Rework loop in the plumbing process

Understandably, effective process time (t_e) is inflated upon the existence of rework and can be computed using Equation (3.1):

$$t_e = \frac{t_0}{1 - p} \qquad (3.1)$$

In Equation (3.1), t_0 is the average processing time and p is the probability of rework. For instance, for the plumbing trade with $t_0 = 3$ days and $p = 25\%$, the effective process time will be $t_e = 4$ days.

Utilisation level of trade contractors is another important performance measure in the construction production and was computed using Equation (3.2):

$$u = \frac{t_e}{t_a} \qquad (3.2)$$

In Equation (3.2), t_a is the average time between activity starts and u is the utilisation level that adopts values between 0 and 100%. Having an effective process time of $t_e = 4$ days, the utilisation level for the plumbing trade will be equal to 80% if new jobs are started every five days.

At the first stage of the analysis, trade contractors with different rework rates were compared when other production variables such as average time between activity starts were fixed. Based on this premise and the collected data, eight observed rework probabilities of 2%, 7%, 10%, 13%, 18%, 25%, 30% and 33% were compared. Tangible performance measures for individual trade contractors were then computed. Table 3.1 shows the results of the analysis.

Table 3.1. Trade-level performance measures with different rework probabilities (p)

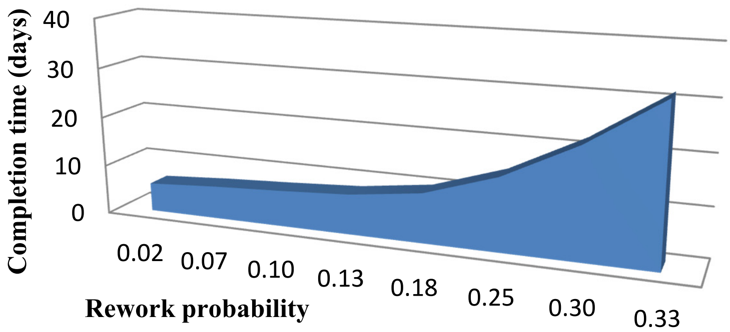
Parameter	**Average time between activity starts (t_a) = 5 days**							
Probability of rework (p)	2%	7%	10%	13%	18%	25%	30%	33%
Effective Process time (t_e)	3.06	3.23	3.33	3.45	3.66	4.00	4.29	4.48
Effective process rate ($r_e = \frac{1}{t_e}$)	0.33	0.31	0.30	0.29	0.27	0.25	0.23	0.22
Utilisation level ($u = \frac{t_e}{t_a}$)	0.61	0.65	0.67	0.69	0.73	0.80	0.86	0.90

As can be seen in table 3.1, both effective process times and utilisation rates grow as the rework probability increases. However, effective process rates of individual trades decreases from 0.33 to 0.22, which shows an increasing amount of waste in the production as a result of workflow variability caused by rework.

Although in the analysed scenarios t_a is fixed, the utilisation level of the trade increases nonlinearly proportional to the rework probability. In other words, the workload of the trade contractor increases despite the fact that the trade contractor does not start new jobs more frequently. This overwhelms the trade contractor when $p > 1 - ({}^{t_0}/_{t_a})$. As can be seen in table 3.1, utilisation level of the trade contractor hits a peak of 90% as the rework rate approaches 33%. When the utilisation level is close to 100%, the trade cannot catch up anymore and successor trades will be delayed.

Understandably, the completion time (CT) of a variable process is always longer than the effective process time as the rework loop may repeat more than once. Furthermore, CT is proportional to the total variability level (V), resource utilisation level (U), and processing time (T). Assuming that arrival processes are moderately variable, queuing theory principles and Kingman's approximation for discrete processes (Kingman 1992) can be used to compute the completion time of the individual trade process. Interested readers can refer to Hopp and Spearman (2008) for a more detailed treatment of the analytical modelling approach.

The surface chart in Figure 3.4 illustrates the results of completion time calculations for different rework probabilities.



	0.02	0.07	0.10	0.13	0.18	0.25	0.30	0.33
Process completion time (days)	5.79	6.67	7.33	8.15	10.00	14.67	22.00	31.43

Figure 3.4. Process completion time for the trade contractors with different probability of rework

As can be seen in Figure 3.4, completion time increases exponentially when probability of rework grows. The findings of analytical modelling at the trade level, extend those of Jarkas and Radosavljevic (2013) and Ummer, Maheswari et al. (2014), highlighting the negative impacts of workflow variability on the production and performance in construction production.

3.4. Impacts of decreasing the interval between starts of new activities at the trade level

In the previous section, the average interval between activity starts (t_a) was fixed. This stabilizes the workflow in the trade contractor network. However, in order to meet the project milestones and make up for the lengthened completion time induced by rework, it is a common approach to reduce the interval between starts. Table 3.2 shows the performance measures in this scenario.

Table 3.2. Trade-level performance measures resulting from reduced activity start intervals

Parameter	**Average time between activity starts (t_a) = 4 days**							
Probability of rework (p)	2%	7%	10%	13%	18%	25%	30%	33%
Effective Process time (t_e)	3.06	3.23	3.33	3.45	3.66	3.95	4.29	4.48
Effective process rate ($r_e = \frac{1}{t_e}$)	0.33	0.31	0.30	0.29	0.27	0.25	0.23	0.22
Utilisation level ($u = \frac{t_e}{t_a}$)	0.77	0.81	0.83	0.86	0.91	0.99	> 1	>1

As is evident in table 3.2, increasing the rework probability and decreasing the interval between activity starts have significant impacts on the performance of the trade contractor.

In order to test if both rework probability and reducing the activity start interval have significant impacts on the process completion time, an analysis of variance was conducted using the General Linear Model (GLM). Probability plots of process completion times show that the data is normally distributed and requirements for analysis of variance are satisfied. Figure 3.5 illustrates the probability plots of process completion times.

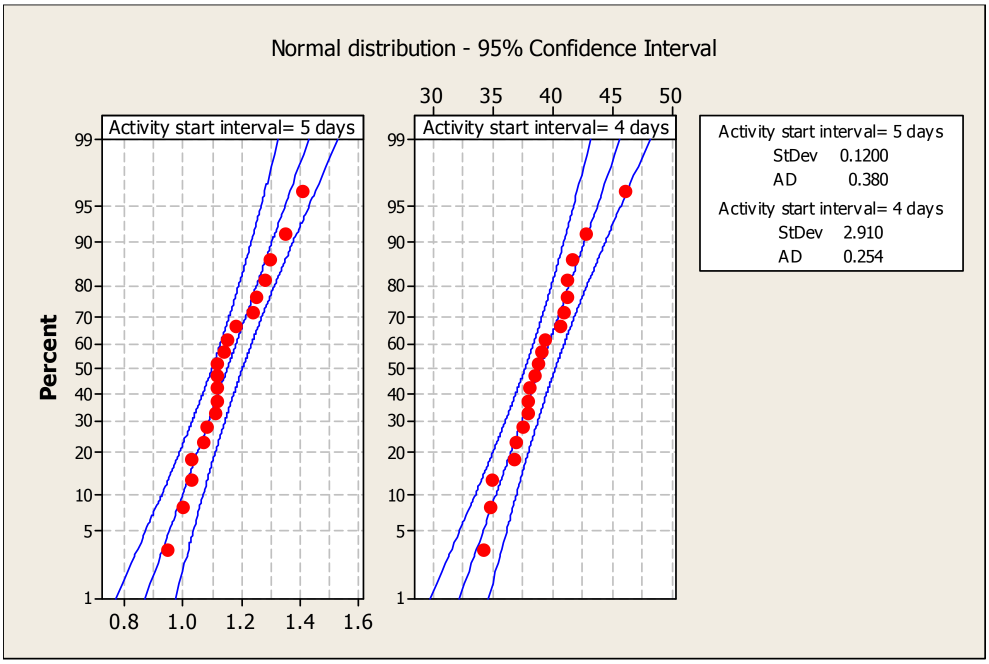


Figure 3.5. Distribution of process completion times

In the general linear model (GLM), response variable is the completion time and factors are rework probability (p) and time between activity starts (t_a). Results of analysis of variance show that both factors have significant impacts on the process completion times. Table 3.3 presents results of this test.

Table 3.3. Results of general linear model (GLM): completion times versus rework probability and rate of job assignment

Source	Freedom degree	Sequential sum of squares	Adjusted sum of squares	Adjusted means squares	F-statistic	P-value
Rework probability (p)	7	6746752	6192340	2064113	1068.78	0.006
Activity start interval (t_a)	1	52574	52574	26287	130.61	0.005

In table 3.3, P-values for both factors are less than the critical value (α = 0.05). Considering the P-value and F-statistic proves that the process completion times significantly differ when rework probability and activity start intervals are variable.

Coming back to results in tables 3.1 and 3.2, a striking difference is noted in the resource utilisation level. Provided that t_a is equal to four days, trades can catch up until rework probabilities are equal to or less than 25 per cent. After this point, the resource utilisation level reaches 100 per cent and the production network becomes unstable. The results show that upon the presence of workflow instability (rework), even a small increase in the rate of activity starts can overwhelm the contractors, causing successor trades to be delayed. This can result in major project schedule overruns, which will be analysed in the next section of this chapter.

The findings extend those of Mahamid, Bruland et al. (2012) and Golob, Bastič et al. (2013), indicating that workflow instability results in inflated completion times and poor performance measures.

Given that residential construction project networks are too complex, not all tangible performance metrics can be computed analytically. The simulation study described in the next section aims to address this limitation. Comparing results of two modelling approaches also provides a validation measure.

3.5. Impacts of workflow variability on the productivity at the project level

The previous analytical results revealed the negative impact of workflow variability on the trade-level performance. This part of the investigation aims to analyse variability impacts on the project-level performance metrics. To this end, simulation experiments were designed and run in order to analyse the data.

The project-level statistics of particular interest are completion time (CT), value added (VA) time, queuing (delay) time, and the level of work-in-process (WIP). Value added time is the duration for a given job to be processed by trade contractors. However, a job is sometimes unattended and undergoes queuing (delay) time because all trades are fully utilised elsewhere, working on other jobs. Using cumulative figures for VA and delays, completion time (CT) for an apartment is computed using Equation (3.3):

$$CT = \sum_{i=0}^{k} (VA + delays) \qquad (3.3)$$

In Equation (3.3), 'k' is the number of interacting trade contractors.

In the discrete event simulation (DES) experiments, trade contractors were not modelled individually but within the interconnected project network. Care was taken to represent details in the construction operations on the worksite. At the first stage, construction production scenarios with different rework rates were analysed. Each scenario was simulated for 100 times in order to achieve the desired statistical confidence level of 95%. Construction processes were simulated for long periods in order to pass transient behaviour and reach a steady state.

Table 3.4 shows the results of running the simulation models.

Table 3.4. Project-level performance measures in different production scenarios

Parameter	**Average time between activity starts (t_a) = 5 days**							
Probability of rework (p)	2%	7%	10%	13%	18%	25%	30%	33%
Completion time (CT)	115.79	133.33	146.67	162.96	200.00	293.33	440.00	628.57
Value added (VA) time	114	114	114	114	114	114	114	114
Queuing time (delays)	1.79	19.33	32.67	48.96	86	179.33	326	514.57
Work-in-process	21.00	24.18	26.60	29.56	36.27	53.20	79.80	114.00

As can be seen in table 3.4, completion times (CT) nonlinearly increase in those production scenarios with a higher probability of rework. Furthermore, the work-in-process (WIP) level builds up and causes congestion in the trade network that again increases delays.

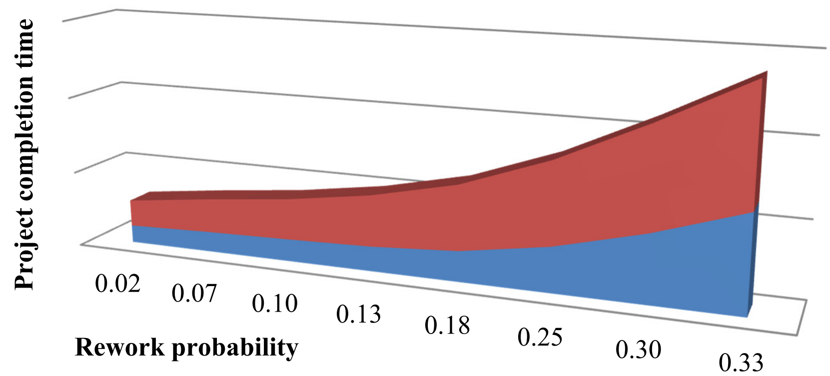
Project-level results are in line with those of the trade-level in the previous section and provide a measure of validation. The findings are consistent with the previous research (Alsehaimi, Koskela et al. 2013, Gündüz, Nielsen et al. 2013), indicating that workflow variability, caused by factors such as rework, is directly translated into long delays and late completions.

Decreasing the activity start intervals in the simulation experiments worsened the performance measures at the project level. Table 3.5 presents the results of running the simulation models in this production scenario.

Table 3.5. Project-level performance measures resulting from reduced activity start intervals

Parameter	**Average time between activity starts (t_a) = 4 days**							
Probability of rework (p)	2%	7%	10%	13%	18%	25%	30%	33%
Completion time (CT)	173.91	222.22	266.67	333.33	420.43	530.55	650.76	756.50
Value added (VA) time	114	114	114	114	114	114	114	114
Queuing time (delays)	59.91	108.22	152.67	219.33	306.43	416.55	536.76	642.5
Work-in-process (WIP)	23.88	30.51	36.62	45.77	57.73	72.85	89.36	128.47

Results in table 3.5 show that reducing the average time between activity starts, increases the work-in-process (WIP) level significantly. Furthermore, longer delays (non-value-added times) in table 3.5 than those in table 3.4, highlight a significant amount of waste in the production processes. In addition, a striking difference is observable in the completion times (CT) by comparing the results in the two tables. Since the average time between activity starts (t_a) is faster in table 3.5, any small increase in the workflow variability, caused by rework, nonlinearly inflates the CT. A comparison of the completion times has been illustrated in Figure 3.6.



	0.02	0.07	0.10	0.13	0.18	0.25	0.30	0.33
Completion time (start intervals= 4 days)	173.91	222.22	266.67	333.33	420.43	530.55	650.76	756.50
Completion time (start intervals= 5 days)	115.79	133.33	146.67	162.96	200.00	293.33	440.00	628.57

Figure 3.6. Completion times in two production scenarios

Previous results in table 3.5 show that decreasing t_a causes the WIP level to grow in a chain reaction, resulting in delays caused by shortage of resources. In fact, construction production networks can become congested (due to higher WIP levels and longer delays) when the workflow is not stable. The findings extend those of Mitropoulos and Nichita (2010) and Liao, O'Brien et al. (2011), indicating that project managers should be extremely cautious about releasing an excessive number of jobs to the network of trades especially when the workflow is subject to any kind of variability such as rework. In other words, solely focusing on process times at the expense of other production variables can lead to unexpected negative results.

3.6. Chapter summary

Prior work has documented the negative impact of variability on performance metrics of construction projects (Tommelein, Riley et al. 1999, Arashpour, Wakefield et al. 2013). However these studies fall short of a holistic approach towards workflow variability and its impacts on both trade-level and project-level productivity and performance. In order to bridge this gap, this chapter quantitatively analysed the impacts workflow variability on tangible performance metrics in several construction production scenarios. Towards this end, mathematical modelling at the trade level and discrete event simulation modelling at the project level were conducted to analyse the data.

The findings clearly show that construction performance and productivity are very sensitive to the interval between activity starts especially when workflow is subject to variability, caused by factors such as rework. That is, an increase in work quantities at the same time as trade involvement in process variability significantly inflates completion times resulting in workflow congestions and wasted time in the interconnected network of trades. These findings extend those of Shen, Jensen et al. (2011) and El-Gohary and Aziz (2014), confirming that performance and productivity in the construction production can be improved through variability reduction and variability buffering approaches. In addition, control of workflow variability can streamline processes within the network of trades, avoiding frequent work overloads or work starvations imposed on trade contractors.

3.7. Chapter contributions and future research opportunity

This chapter contributes to the body of knowledge in engineering management by developing an insight into the dynamics of workflow variability and its impact on construction productivity and performance. Most notably it is one of few studies to our knowledge that takes a holistic approach towards analysis of both trade-level and project-level performance using both analytical and simulation modelling. The results provide compelling evidence that excessive system loading together with workflow variability results in work congestions and productivity loss. It is suggested that project managers avoid assigning excessive levels of work quantities to trade contractors when the workflow is subject to variability. This chapter reveals the tip of the iceberg in performance-related issues in the construction production. Further research should analyse other management-related variables that affect the construction production and identify feasible interventions in order to control their effects on performance and productivity. Furthermore, variability effects on the entire supply chain of the construction projects could also be investigated.

4. Chapter Four – Modelling variability in the flow of work (hand-offs) amongst specialty contractors

4.1. Introduction

Chapter three investigated impacts of workflow variability on productivity and performance in construction production and it was found that workflow variability causes poor performance reflected by long completion times and insufficient utilisation of resources. FULFIL analysis showed that adverse effects of workflow variability is more pronounced in construction networks with high levels of work-in-process as work starvations and work overloads are more likely to happen. This chapter aims to meet the second research objective and find a tailored modelling approach in order to quantify the level of workflow variability in construction networks. Models developed in chapter four form an important part of the FULFIL system to diagnose and measure workflow variability in the construction production.

The construction industry is plagued by long cycle times caused by variability in the workflow. Variations or undesirable situations are the result of factors such as non-standard practices, work site accidents, inclement weather conditions, faults in design and rework. This chapter uses a new approach for modelling variability in construction by linking relative variability indicators to processes. The mass house building sector was chosen as the scope of the analysis because it is a very data-rich environment. Numerous simulation experiments were designed by varying size of capacity buffers in front of trade contractors, availability of trade contractors, and level of variability in house building processes.

Simulation of construction processes has received much attention in recent years due to its ability to estimate the behaviour of system upon the presence of variability. Variations or undesirable situations that arise are the result of delays or interruptions in the workflow. Performance measures such as project completion time or resource utilisation rates are very sensitive to changes in production variables.

Attention should be paid to address present variability in production systems otherwise the cost will be paid later on in forms of lost output (throughput) rate, wasted capacity, inflated completion (cycle) times, and poor customer service (Arashpour and Arashpour 2012).

Construction processes are different in nature with unequal levels of variability. In residential construction, for instance, an outdoor process such as roofing is more prone to inclement weather conditions comparing with an indoor process such as plumbing. Also, other factors such as accident risk differ from one process to another. In the construction management literature, some researchers have modelled the variability by means of longer mean process times (Walker and Shen 2002, Walsh, Sawhney et al. 2007, Arashpour, Wakefield et al. 2013) and some others by assuming a larger variance in process times (Peña-Mora and Dwivedi 2002, Sawhney, Walsh et al. 2009, Ghoddousi, Eshtehardian et al. 2013). However, the negative influence of variability has been more precisely modelled in other sectors such as manufacturing. Using relative measures of variability have led to a more accurate measurement of system performance in the manufacturing sector (Hopp and Spearman 2008, Jeong, Hastak et al. 2011).

Evidences such as lengthened completion times and poor client service particularly during boom periods calls for new approaches for variability modelling in construction projects (Cates 2004). On this basis, the present chapter uses an innovative approach for modelling variability in residential projects by linking variability indicators to processes. A two-level hierarchical model was developed to represent the typical production of detached suburban houses in Melbourne, Australia. Numerous simulation experiments were then conducted by varying: 1. Size of the buffers (queue of jobs to be processed) in front of trade contractors; 2. Level of resource availability; and 3. Variability level in the production house building network. In this chapter, the effects of variability on the key performance measures such as project completion times and resource utilisation rates are explored.

4.2. Review of the existing approaches to model/address variability in the construction industry

Data obtained in previous studies indicate that variability, which is non-uniformity in building processes, always degrades the performance and productivity measures in construction projects (Moyal 2010, Chia, Skitmore et al. 2012). Existing strategies are discussed in the following sections.

4.2.1. Using capacity buffers against production variability

Construction processes are usually defined by the trade contractors who are responsible for them. Buffers between processes can prevent downstream trade contractors from becoming idle when upstream contractors experience a delay (González, Alarcón et al. 2011, Koskela and Ballard 2012). Disadvantages of large buffers between interacting trade contractors include a large work-in-process (WIP) inventory and higher costs. In order to investigate this approach to model and address variability, different capacity buffer sizes are modelled and compared in the first and second scenarios.

4.2.2. Increasing resource availability

Availability of the trade contractors can directly affect the completion time of construction processes. During boom periods, house builders often use more trade contractors or overtime as buffers against undesirable situations in the work sites (Arashpour, Shabanikia et al. 2012). By authorization of over time the work capacity increases temporarily and overtakes the demand rate. However, overtime will be required in a cyclic manner as there is always randomness in demand and production rates (Hopp and Spearman 2004). Any change in availability of resources has an impact on costs, similar to the crashing concept in project planning. The third scenario in this chapter focuses on resource availability.

4.2.3. Variability reduction approaches

Different approaches are available to reduce the variability level in the mass production house building sector. For example, using modular designs can decrease completion times of onsite operations. Furthermore, using prefabrication, modularization and preassembly can dramatically improve constructability (Blismas, Wakefield et al. 2010). Another initiative is to use advanced design and marketing methods, which enables the construction firms to schedule the production in advance (Bouchlaghem, Shang et al. 2005, Veryzer 2005).

Flow-smoothing is another way of reducing variability in the construction environment. Different techniques can be used for this aim such as standardizing construction practices (Carlos, Dos Santos et al. 2002), quality management and reducing rework (Henry 2000), and applications of lean principles in industrialized housing production (Ballard and Howell 1994, Zimina, Ballard et al. 2012). Furthermore, variability caused by project-based subcontractors can be decreased by developing long-term business relationships with them. In this way, much of the capacity buffer against variability is carried by subcontractors (Kumaraswamy and Matthews 2000, Greenwood 2001). The variability reduction approach has been modelled and analysed in the fourth scenario.

4.3. Research design

Interconnected work processes are main building blocks of construction projects. They are performed either serially or in parallel until the project is completed. In the first step of this study, process times were plotted for main processes in volume house building projects (see Figure 4.1). Then, statistical parameters of the data were calculated to perform a chi-square check (Halpin and Woodhead 1976, Love, Sing et al. 2013). Care was taken to match the process times to the optimum statistical distribution.

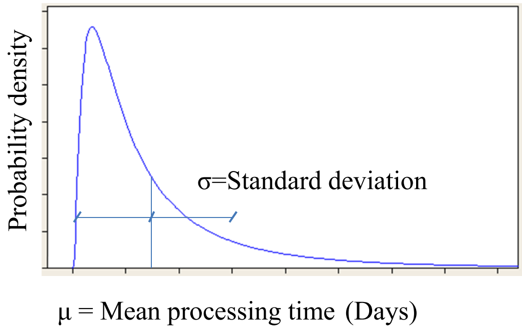


Figure 4.1. Probability density of cycle times in the construction production system

In the next step, the house building model was developed using similar method to Bashford, Sawhney et al. (2003). ARENA simulation software was selected for modelling due to its flexibility in using both ready-to-use constructs and user-written codes by general-purpose procedural language of SIMAN. User-written codes enable precise modelling of unique situations in the production house building sector such as several hand-offs (workflows) among trade contractors. Numerous experiments were designed by varying the size of the capacity buffer between trade contractors, availability level of trade contractors, and level of variability in house building processes.

A new indicator to measure the relative (not absolute) variability was introduced and used in simulation experiments. Then, results were validated against Little's law, which is a basic equation used in manufacturing management.

4.4. Case study

The typical process of building suburban houses in Melbourne, Australia was modelled. A good track of the production data is usually kept in the volume house building sector, which makes it an ideal scope for our investigation. Allocating an ID code to each trade contractor enabled us to trace upstream and downstream processes and analyse the effects of resource availability on them. In the Australian volume house building scenario, all the main building processes are subcontracted to trade contractors. Table 4.1 shows the list of operations for 20 selected subcontractors.

In production house building environment, the builder is solely focused on sales and construction management. Subcontractors are in charge of performing construction operations (Walsh, Bashford et al. 2004). Due to congestion in work sites, subcontractors are required to finish their job quickly and vacate the workface for next contractors. The transfers of work among trade contractors are sometimes called 'hand-offs' and becomes more complicated with an increasing number of involved trade contractors.

Table 4.1. Selected house building processes and the ID for responsible trade contractors

Process	Subcontractor ID	Process	Subcontractor ID
Site preparation	1	Drywall	11
Foundation	2	Trim carpentry	12
Framing	3	Plumbing fit-out	13
Brickworks	4	Electrical fit-out	14
Roofing	5	Painting	15
HVAC rough in	6	Tiling	16
Plumbing rough in	7	Flooring	17
Electrical rough in	8	External paving	18
Cladding	9	Cleaning	19
Insulation	10	Finishing and handover	20

In order to identify different labour resources in designing simulation experiments, a unique ID is dedicated to each trade (see Table 4.1). The simulation method is a suitable approach to empirical work as it is very costly to experiment with real systems and examine (pre-test and post-test) their behaviour upon changes in input variables (Fellows and Liu 2008, Martinez 2010). Despite the fact that performance measures in simulated systems involving variability might be subject to error, long simulation runs allow production systems to stabilize and achieve reliable outputs (Hopp and Spearman 2008).

It is worth mentioning that all models are abstractions of reality. While there is a considerable debate about how realistic the assumptions of a model need to be, there is a general agreement on accurate prediction as the major aim of any model. In this way, the validity of assumptions is of secondary importance. A useful theory should be judged not by its descriptive realism but by its simplicity and fruitfulness as an engine of prediction (Friedman 1953). In other words, the value of a model is an empirical question – how useful it is, and how well it predicts. Therefore, the validity of a model cannot be settled by theoretical arguments but only by empirical investigations.

4.4.1. Variability in process times

The mean time (μ) for a construction process is not fixed and there is always variability around each process. The variability can be caused by several factors such as queuing time to use resources, rework, inclement weather conditions, and accidents on the work site. Both commonly used parameters of mean (μ) and standard deviation (σ) of construction process times reflect absolute variability. However, relative variability is more important in the production environment (Hopp, Iravani et al. 2011). As an example, consider a 2 mm dimension error that is not critical in the thickness of footings. The same error, however, can affect the stability and internal tensions of structural elements if it is a deviation from the vertical access of columns. Therefore, a relative Variability Indicator (VI) can be a very robust parameter in analysing construction processes. VI can be calculated using Equation (4.1),

$$VI = \frac{\sigma}{\mu} \qquad (4.1)$$

In Equation (4.1), σ is the standard deviation of time between completions (process) and μ is the mean processing time. Variability indicator does a similar measurement to the coefficient of variation in manufacturing production (Hopp and Spearman 2008). The key contribution of the proposed approach is to enable house builders to evaluate the long term performance of trade contractors and consider both mean and standard deviation of process times.

Trade contractors closely interact in the interconnected network of projects. In this way, the departure rate (r_d) of a predecessor is the arrival rate (r_a) for its successor:

$$r_d(subcontractor\#1) = r_a(subcontractor\ \#2) \qquad (4.2)$$

A schematic illustration of the interconnected trades can be seen in the Figure 4.2.

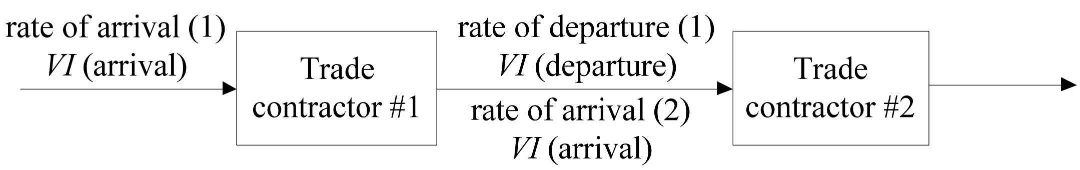


Figure 4.2. Illustration of the flow of work between trade contractors

Since several interacting contractors are involved in the complex operations of house building, it is logical to consider the maximum randomness for completion times and also job arrival rates.

That is, the mean and standard deviation of construction process times can be represented by exponential distribution ($VI = 1$). In this way, once a trade contractor undergoes a very long process time due to bad weather conditions or an accident in the work site, the following trade contractor becomes idle. Similarly, very long process time for a successor will result in blockage of the predecessor if the builder does not allow having long queues of uncompleted jobs in the network.

4.4.2. Size of the capacity buffers in front of each trade contractor

In the absence of variability, the optimum number of houses under construction is equal to the number of trade contractors. This minimises the completion time and keeps every trade contractor busy at all times. This special level of work-in-process (WIP) inventory is called critical work-in-process (w_0). Upon the presence of variability, average completion time of each house will inflate. To improve the situation, the first two scenarios are analysed in order to find the optimum size of the capacity buffers in order to optimize tangible performance measures: system throughput rate (TH), house completion time (CT), and the number of houses under construction (WIP).

In the first scenario, size of the capacity buffers in front of each trade contractor is quite large and up to 3 houses can stand in a queue to be processed. Exponentially distributed process times introduce the maximum randomness to construction operations.

In the second scenario, size of the capacity buffers is decreased to only one house. It is worth mentioning that the policy used here is very similar to Kanban squares that are used in manufacturing production lines. In each scenario $\frac{WIP}{w_0}$ was calculated in order to quantitatively determine how efficient the house building network is working.

4.4.3. Number of trade contractors (resource availability)

In the third scenario, construction processes were accelerated by increasing the resource availability level. Using two dedicated (available for 100 per cent of time) trade contractors for each process resulted in the mean processing time decreasing to almost half. Similar to the second scenario, a small capacity buffer of one job in front of each trade contractor was used.

4.4.4. Level of variability in construction process times

In the previous scenarios, we assumed the presence of maximum randomness in the house building network ($VI = 1$). Variability can be decreased by smoothing the work flow, upgrading the quality of operations in order to minimise the amount of rework, avoid delaying successors, and reducing accidents by means of improved safety measures (Anumba and Bishop 1997, Arashpour and Arashpour 2010). The variability Indicator (VI) of the processes was decreased from 1 to half in the fourth scenario. Trade contractors can move to a new class of variability by reducing the ratio of mean process time to standard deviation over the long term.

4.5. Output analysis in different scenarios

Care has been taken to build models with the closest possible similarity to the typical house building setting in Melbourne, Australia. For this reason, input analysis on the collected data was conducted to fit them with the best-matching probability distribution. Each production scenario was replicated 100 times in order to achieve statistical accuracy in the results. The desired confidence interval was 95% in the experimental design. The scenarios were run for 1000 working days. Table 4.2 illustrates quantitative comparison of average performance metrics in production runs.

Table 4.2. Performance measures of the volume house building network in the four production scenarios

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Size of the capacity buffer	3	1	1	1 (houses)
Variability indicator (VI)	1	1	1	0.5
Average throughput rate (TH)	0.55	0.54	0.56	0.58
Resource utilisation rate	91.8%	89%	93%	96%
Average cycle time (CT)	195	135	115	120 (days)
WIP inventory (houses)	36	24	22	23
Per cent of the optimum WIP	180%	122%	110%	116%

In order to cross-check the precision and validation of results, the outputs of simulation modelling were compared with an analytical model. Due to the long simulation period, which let the production network to reach its steady state, Little's law was selected. Little's law is a queuing formula, which is widely used in manufacturing, in order to predict the performance measures of steady state systems over the long run (Little 1961, Little 2011). It correlates the work-in-process inventory (WIP) to the throughput (TH) rate and completion time (CT):

$$WIP = TH \times CT \qquad (4.3)$$

A two-sample t-test was conducted and no statistically significant difference was found between the performance measures computed by simulation and the analytical model. Table 4.3 illustrates the results for one of the measures.

Table 4.3. Comparison of simulation and analytical results

Scenario	WIP inventory (simulation results)	WIP inventory (analytical results)	Error percentage
1	36	35.7	0.8%
2	24	24.1	0.4%
3	22	21.8	0.9%
4	23	23.2	0.8%

As can be seen, running the simulation over the long term caused the system to stabilise and consequently our results complied with Little's law.

4.6.Relationship between capacity buffer and production parameters

In the first scenario and by using a capacity buffer of three houses, the number of homes under construction reached a peak of 36. Consequently, the average cycle time for a single house was inflated to 195 days, as it is evident in table 4.2. This indicates that although capacity buffers prevent downstream contractors from work starvations and idleness, increasing the number of houses under construction results in lengthened completion times. There is a similar situation during construction boom periods, when demand exceeds the capacity of trade networks and houses have to stand idle before being progressed (Gharaie 2011). Large capacity buffers create a big WIP inventory resulting in late completions and decreased service level.

In scenario 2 and by decreasing the size of capacity buffers in front of trade contractors to 1 house, average completion times decreased dramatically. It is worth mentioning that no extra resources and investment are needed. Improvements in this scenario are the results of changing the control and management policies by limiting the size of capacity buffers. In the second scenario, the number of houses under construction declined to 24, which reduced the average completion time to 135 days (see table 4.2). The construction output rate (TH) is slightly less than TH in the first production scenario. This is because of occasional job starvations that downstream trade contractors undergo.

4.7.Relationship between resource availability and production parameters

In the third scenario and by increasing the level of resource availability, the average house completion time decreased to 115 days. Although the third scenario achieved the shortest average CT, trade-offs need to be made as reducing the mean value of construction process times here is linked to employing more trade contractors and costs might offset the profits (unlike the second scenario with no extra costs).

4.8. Relationship between variability indicator and production parameters: Applications of the new variability modelling approach

The relative variability indicator introduced in this study can measure the true efficiency of construction processes. Different policies can be used by trade contractors to reduce the variability indicator (VI). These include avoiding rework by improving quality controls and preventing workflow interruption by improving safety measures.

In the fourth scenario and by reducing the variability indicator to half, a completion time of 120 days was achieved, which is almost identical to the third scenario with its necessary investments. Number of houses under construction is 23, which is surprisingly very close to the optimum level of WIP. In fact, there is almost no capacity buffer in front of the trade contractors). In this scenario, the house building network worked efficiently without the need to invest on more resources.

Overall, although there are several opportunities in construction sites to *buffer* against variability, the most advantageous approach is the hard work of variability *reduction*. Successful variability reduction strategies, although with custom-designed policies, could be implemented in future projects of a firm (Hopp and Spearman 2008). Additionally, improving a specific construction process by finding the source of excess variability would create the mind-set of variability reduction and environment of continual improvement within the house building networks (Arashpour and Farzanehfar 2011).

4.9. Chapter summary

Data obtained in previous studies indicate that variability is not accurately modelled and addressed in construction projects. This fact in the mass house building sector results in inflated house completion times, reduction in outputs, and more capital costs for homebuyers (Bashford, Walsh et al. 2005, Arashpour, Wakefield et al. 2013). In the construction management literature, variability has been mostly modelled by assuming longer process times (pessimistic durations) and/or a larger variance in process times.

In order to bridge this gap, the present chapter modelled the variability in the production house building sector using an innovative approach. Numerous experiments were designed by varying size of the capacity buffers between trade contractors, availability of trade contractors, and the intensity of the variability indicator in house building processes. The findings extend those of Kamat and Martinez (2008) and Li, Chan et al. (2009), confirming that tracing, modelling and addressing sources of variability in construction can lead to achieving optimum performance measures.

4.10. Chapter contributions and future research opportunity

The key contribution of the proposed approach is to enable house builders to evaluate the long term performance of their trade contractors and decide on the best size of the capacity buffers (queue length of houses to be processed) in front of each trade. Due to similarities in construction production environments, results are likely to be generalizable to other subsectors of the industry.

Future research could include works designed to model variability and investigate its effects on production parameters. The variables within construction projects are countless and underlying logics for many system behaviours in the construction sector are still unknown.

5. Chapter Five – Stabilising the workflow in construction production networks

5.1. Introduction

Chapter four established a tailored approach for modelling variability in the construction production environment. It was found that variability is contiguous and is transferred from processes of precedent trades to processes of successor trades. In other words, specialty trades are interacting in an interconnected production network and their performance is not independent of each other. This chapter aims to address the third research objective and analyse impacts of workflow variability on variability reduction. Findings of chapter five are closely related to the FULFIL variability management system that is introduced in chapters six, seven and eight.

Subcontracting has been widely used in the construction industry in order to address the high level of variability and associated risks. However, the explosion of subcontracting and the parade of trades have made the construction operations very fragmented, leading to a lack of predictability and adequate control on schedules and quality (Tommelein, Riley et al. 1999).

To manage a construction system effectively, it is necessary to understand its configuration first. Among the construction subsectors, residential construction has many similarities to manufacturing (Bashford, Walsh et al. 2003). In other words, it is possible to look at residential construction as a production line, with almost similar production problems to manufacturing. For example, in boom periods when the demand for building houses peaks, trade contractors in the house building network are flooded by a large number of houses to be built. Understandably, this high level of work-in-process inventory (WIP) will lengthen the cycle time (CT), which is the average time between the start and end of construction operations. This is due to limited capacity of the construction systems.

Similar to machine failures in a manufacturing setting, events such as worker fatigue or illness, equipment breakdown, and shortage of material supply can impose delays or interruptions on individual processes (trade level). Furthermore, exogenous events such as inclement weather conditions, inefficient construction management decisions, and industrial actions can affect the operations at the project level (Damrianant and Wakefield 2000). These reduce the output rate or throughput (TH) of the system.

To address the high level of variability and resulting risks, subcontracting has been widely used in the complex configuration of residential construction production systems. House builders, who generally act as the construction manager, subcontract all or most of the production processes. In the most common scenario in the Australian residential construction, around 50 trade contractors are in charge of more than 100 building processes in order to build a typical suburban house. In this way, the risk of delays and late completion is generally avoided by the builder and is transferred to trade contractors as they are usually paid upon the completion of activities (Arashpour and Arashpour 2012). However, the explosion of subcontracting and the parade of trades have made the management of these fragmented networks very difficult, leading to a lack of predictability and adequate control on schedules and quality (Dalton, Hurley et al. 2013). The final result is the significant holding cost for capital that is generally borne by homebuyers due to extended cycle times and pre-occupancy periods.

Although many attempts have been made by construction management professionals to improve the situation within the present system configuration, little attention has been paid to reconfigure the system. In order to bridge this gap, this chapter analyses the implications of two even flow production principles. Principles of even flow production have been successfully implemented in large housing projects in the U.S. (Bashford, Sawhney et al. 2003). Even flow production known as workflow-levelling strategy aims to stabilise the workflow amongst trade contractors.

Two flow smoothing initiatives and their effect on project performance measures are tested in this chapter: Maintaining a constant number of houses under construction (Constant work-in-process (CONWIP)), and adding flexibility to movement of jobs (hand-offs) by means of integrating work processes and cross-training trade contractors.

5.2. Research methodology

The positive effects of even flow production have been investigated in manufacturing (Hopp and Spearman 2008). However, their impact on construction production needs more scrutiny (Bashford, Sawhney et al. 2003). In order to bridge this gap, volume house building in Australia was studied and numerous simulation experiments were designed by varying the number of trade contractors, rate of starting new homes, process times, and standard deviation of time between completions. Care was taken to realistically model major production house building elements. The scenarios were simulated for 100 times each, in order to achieve statistical precision in comparing and contrasting tangible performance measures. Figure 5.1 shows the simulated model of house building network.

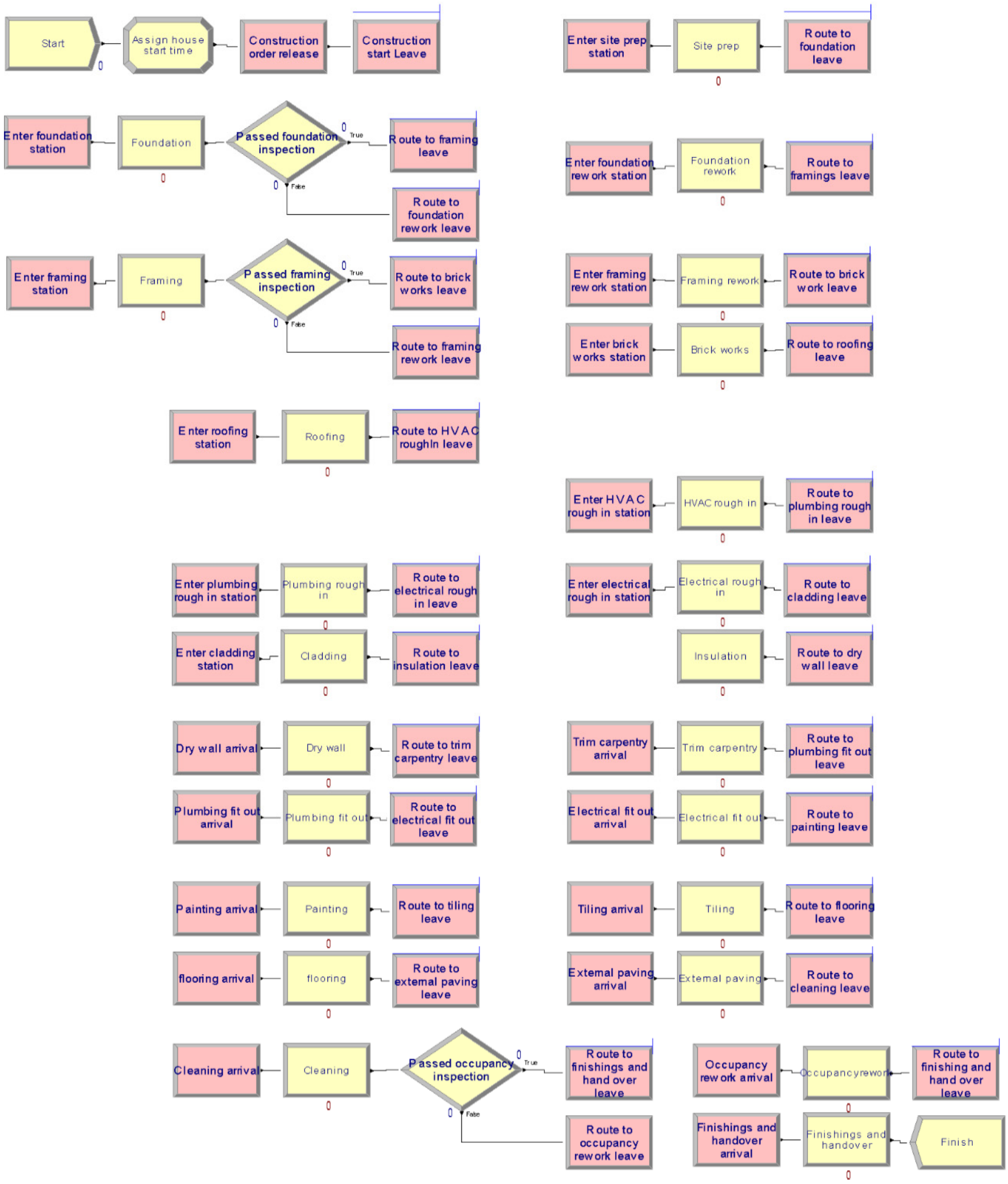


Figure 5.1. Interacting specialty trades in the simulation model of the house building network

This simplified model of production house building was developed in order to demonstrate movement of jobs (workflow) among trade contractors and interaction of different resources. In the first scenario (base case), the level of variability is assumed to be very low and therefore both process times and starting rate of new houses have uniform distributions. However, in the second scenario this assumption is relaxed and sales rates determine the start pace of new constructions. This is a typical practice in push production or so called due date driven systems. In the third scenario, the rate of starting new houses is controlled and a CONWIP protocol is used to maintain a constant number of houses under construction at all times. Finally, in the fourth scenario, the number of specialty trades is reduced by using cross-trained contractors instead.

5.3. Results and analysis

5.3.1. Scenario 1- uniform process times and start rate

Assuming a very low level of variability, the first scenario yields the best performance measures. In this scenario, each of the trade contractors in figure 5.1 needs a fixed duration of time in order to complete their processes. Therefore, the throughput rate of the network is equal to $1/T_0$ (house/day). T_0 is the average time that a single house takes to traverse the construction production network and is equal to 140 days, based on the collected data.

Other production parameters can be computed using Little's law (Little 1961), which is a basic equation used in manufacturing:

$$TH = WIP/CT \qquad (5.1)$$

In Equation (5.1), TH represents the throughput (output rate) of the network; WIP is the number of houses under construction (work-in-process inventory); and CT represents the average time for completing a house.

In the absence of variability, the optimum number of houses under construction can be computed in a similar approach to Hopp and Spearman (2004).

$$WIP_{critical} = r_b \times T_0 \qquad (5.2)$$

In Equation (5.2), $WIP_{critical}$ is the optimum number of houses under construction and r_b is the production rate of the bottleneck. Having $WIP_{critical}$ in the network guarantees a minimum cycle time and optimum utilisation of labour resources (trade contractors).

Based on the production data and using Equation (5.2), having an inventory of 20 houses under construction in the first scenario results in building up no queues and efficient behaviour of the system.

5.3.2. Scenario 2- Push production (Due date driven construction)

During construction boom periods, when demand for building new houses peaks, trade networks are flooded by large number of houses under construction (work-in-process inventories). As is the common practice in the industry, builders usually set high levels of WIP in order to increase utilisation rate of trade contractors and achieve a throughput rate close to the capacity of the trade network. However, this approach will cause cycle times to grow infinitely because of the limited production capacity. Although adding resources will temporarily improve the performance measures of the system (Aziz, Anumba et al. 2009, Arashpour and Arashpour 2010), it would not financially or spatially be feasible in all cases.

The second scenario realises the fact that several production detractors are present in construction sites such as worker fatigue or illness, equipment breakdown, shortage of material supply and inclement weather conditions. Taking these into consideration, random process times in the second scenario were modelled and analysed. Input analyser function in the ARENA simulation system was used in order to find the best-fitting probability distribution for the collected data. In this way, the probability that a process can be completed on-time is defined realistically. For example, Figure 5.2 shows that Gamma distribution with a shape factor of 2.533 and a scale factor of 5.999 can best represent the rate of starting new jobs or random inter-arrival times.

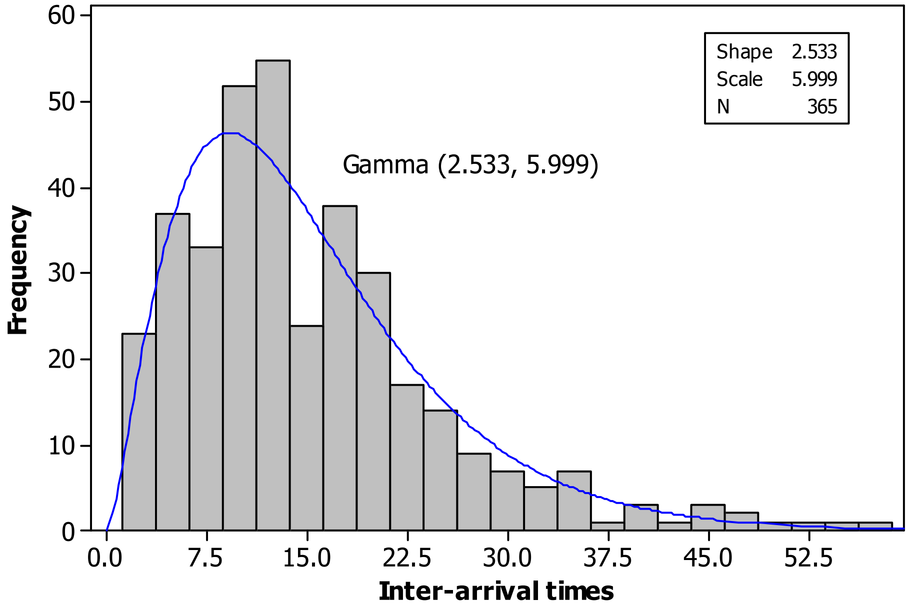


Figure 5.2. Histogram of collected data on random inter-arrival times and the best-matching probability distribution

Understandably, when number of specialty trades is equal to *N,* a newly started house in the network is expected to stand in a queue behind $(WIP - 1)/N$ other houses waiting to be processed. In the second scenario, demand rates were also considered to be random and occurred according to an exponential probability distribution. In contrast to the previous case, new jobs are pushed into the system regardless of the current system state or WIP inventory level. The average level of WIP inventory reached a peak of 39 houses in the current scenario. As expected and due to finite capacity of the trade network, the completion time (CT) of houses increased dramatically.

5.3.3. Scenario 3- Maintaining a constant number of houses under construction (CONWIP protocol for production control)

In the third scenario, care was taken to maintain the constant number of houses under construction at all times. That is, the construction of a new house will not be authorised until a completed house exits the trade network. Assuming a similar processing time for trades (balanced network), the average processing time by a trade for a house i is represented by T_i and can be computed by Equation (5.3),

$$T_i = t + (\frac{WIP - 1}{N}) \times t \tag{5.3}$$

In equation (5.3), t is the processing time for a trade and $\frac{WIP-1}{N}$ is the queue length in front of a trade. Finally, the average completion time (CT) for a house will be,

$$CT = \sum_{i=1}^{N} Ti \tag{5.4}$$

Assumptions made to model the construction production analytically are not used in the simulation models. Results of analytical and simulation modelling are very close and provide a measure of validation for the analysis

Calculating the performance measures of the trade network, the throughput rate in the third scenario is more than push production in the second scenario. Also the average completion time for a house in the third scenario stood at 273 days, which is considerably less than 395 days in the second scenario. Figure 5.3 compares the number of houses under construction (WIP inventory) versus throughput in these scenarios.

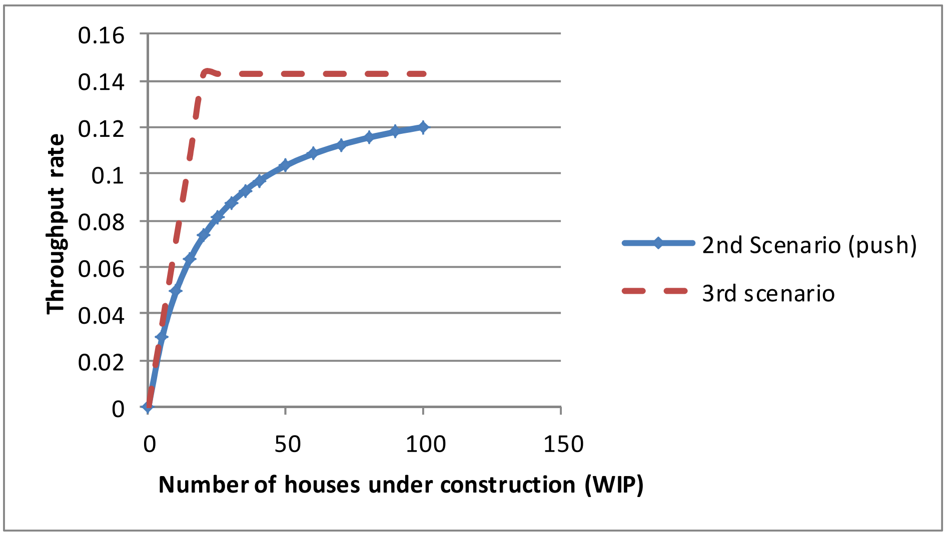


Figure 5.3. Work-in-process inventory versus throughput- Base case vs. push production

Based on the measurements, controlling number of houses under construction (work-in-process inventory) showed to have significant positive effects on performance metrics of the house building network.

5.3.4. Scenario 4- Flexible system with integrated work processes using cross-trained contractors

Excessive number of trade contractors in the system makes it difficult to manage handoffs among predecessors and successors. A solution would be to collapse work processes by using cross-trained trades (Tekin, Hopp et al. 2009). In other words, replacing single specialised trade contractors with parallel cross-trained contractors with the same capacity can improve performance. Such production systems were typical of the residential construction industry in the past, when a sole builder was in charge of all processes and was responsible to the homebuyer.

In the fourth scenario, work processes were collapsed into integrated processes. That is, the first contractor, for instance, was in charge of site preparation and concreting the foundation slab. Therefore, instead of using two specialised contractors to undertake site preparation and foundation processes, two cross-trained contractors are working in parallel, both able to do the two processes. Understandably, process times were assumed to be twice as long as the other scenarios in order to have a fair cross-scenario comparison.

5.4. Discussion

Data obtained in previous studies indicated that workflow levelling principles known as even flow production can improve production efficiencies considerably. According to Bashford, Walsh et al. (2003), even flow strategies have positive impacts on both completion times and management efforts. In addition to the analytical models developed in this chapter, a series of simulation experiments were used to implement two flow smoothing initiatives: maintaining a constant number of houses under construction (CONWIP) and integrated work processes. Table 5.1 shows the results obtained from simulating the house building network over long production runs.

Table 5.1. Tangible performance measures of the house building network in the four scenarios

Parameters	***Scenario 1***	***Scenario 2***	***Scenario 3***	***Scenario 4***
Process times	Uniform	Random	Random	Random
Production description	Low variability	Push Production	CONWIP	Flexible
No. of houses under construction	20	39	20	20
Average waiting time of a house for a trade	0	13.6	6.65	0
Average house completion time (CT)	140	395	273	127 (days)
House completion intervals	7	15.4	13.7	7.14

As can be seen in table 5.1, the first simulation experiment yielded the best throughput rate because there was no variability in process times. This best performance served as the benchmark in order to evaluate production parameters in other scenarios.

The push production approach used in the second scenario downgraded tangible performance measures in the house building networks. The average waiting time for a house to be processed by a trade reached a peak of 13.6 days resulting an average completion time of 395 days for a house. The findings confirm those of Gharaie (2011), indicating that increasing the number of houses under construction in a resource constrained production environment causes long delays.

Limiting the number of houses under construction (constant work-in-process) resulted in better performance metrics than the push production. This is consistent with results obtained in previous studies (Bashford, Walsh et al. 2003). Furthermore, a dramatic improvement in production parameters was observed when integrated work processes were used in the fourth scenario.

House completion intervals in the fourth scenario are almost similar to those in the first scenario (Base case with no variability in processes). This indicates that reducing the number of interacting trade contractors can reduce the workflow variability and improve tangible performance measures in the house building network. Using cross-trained contractors decreased the complexity of the system by means of reducing the number of work overloads and starvations.

Overall, results obtained in this chapter show that implementing two workflow smoothing principles can considerably improve tangible performance measures in the house building networks. These principle are maintaining a constant level of work-in-process (CONWIP) and integrating work processes.

5.5. Chapter summary

Prior work has documented several problems in construction production and the efforts to model and address those. In order to mitigate high levels of variability and resultant risks in construction production, subcontracting has been widely used. While attempts have been made by construction management professionals to improve the situation within the present system configuration, little attention has been paid to stabilise the workflow between interacting trades in order to improve performance metrics.

This chapter focused on implementing two principles of stabilising the workflow in construction production. Firstly, limiting the number of jobs under construction prevented long queues within the network of trade contractors. Secondly, employing cross-trained contractors was found to significantly improve tangible performance measures by means of reducing the number of work starvations/overloads. These initiatives help to better manage the handoffs among trade contractors and reduce the workflow variability. The finding extends those of Dalton, Hurley et al. (2013), confirming that faster, more predictable systems in the residential construction sector tend to have more simplified configurations. Implementing such initiatives are more cost effective than adding more resources during the boom periods because efficiency is all about the how of converting WIP inventory to throughput.

Variability reductions caused by stabilising the workflow between trade contractors can result in significant savings in holding cost for capital that is generally borne by clients.

6. Chapter Six – Variability reduction in the FULFIL system of production control

6.1. Introduction

Chapter five focused on stabilising the workflow in construction production networks and the resulting variability reduction. It was found that a stable workflow will improve the performance reflected by shorter completion times and a balanced utilisation of resources. The fourth objective of the thesis is to investigate and propose workflow management approaches that can reduce variability and its negative effects in construction production. The negative effects of variability were explored as the first objective of the thesis. In order to achieve the fourth objective, two workflow management strategies of rate-driven and due-date-driven production are analysed and compared. In chapter six, variability reduction in construction projects is investigated and implications for efficiency, supervision and controllability of construction production are explored. This chapter analysed the theoretical and practical reasons behind efficiency improvements in pull production together with the CONWIP workflow control protocol. Findings of this chapter form the first part of workflow variability management in the FULFIL system. Remaining variability in production networks is buffered against and will be treated in detail in chapter seven.

Concerns about efficiency, quality and affordability in the residential construction indicate that there may be benefits in adopting alternative production control strategies to those traditionally used. Reducing adverse effects of exogenous variability in demand and endogenous variability in process are the ultimate goals of production strategies. For residential construction this means controlling the number of houses under construction and controlling the start rate of new house constructions. The aim of this chapter is to compare and contrast the outcomes of these two production management strategies.

House building is an important segment of the construction industry that heavily relies on subcontracting. Because operations in the interconnected network of trade contractors are very repetitive in nature, even small efficiency improvements can increase profit margins substantially (Lucko 2010). Principles of production management have been borrowed from manufacturing to improve traditional methods of construction project management. For example, resource driven scheduling or Critical Chain Project Management (CCPM), which is based on the theory of constraints (Goldratt and Cox 2005), adds more accuracy to the Critical Path Method (Del la Garza and Kyunghwan 2009). Furthermore, lean construction (Ballard and Howell 1994, Sacks, Treckmann et al. 2009) and even flow production (Bashford, Sawhney et al. 2003) are being increasingly cited in the construction management literature as means of optimizing performance measures such as lead time, profit, output/throughput (TH), and service level.

The objective of the workflow management or even flow production (EFP) is to ensure a smooth workflow among several interacting trade contractors by means of reducing the variability in their workload caused by fluctuating sales rates. In construction, EFP was first used to study house building projects in Phoenix Arizona (Bashford, Sawhney et al. 2003), where superiority of EFP in terms of minimizing house completion times , workflow variability, and management efforts was confirmed.

There are two differing strategies for system loading in resource-constrained networks of production house building, each with unique effects on performance measures (Bashford, Walsh et al. 2005). The first, and traditional, method to manage system loading in the volume house building is due date driven and based on the sales rate, where builders push new jobs into the network so that it matches the sales. This strategy of push production fails to maintain house completion times at a reasonable level and also creates an unsustainable production flow especially during boom periods, when demand for building new houses increases substantially and resource constrained trades cannot keep up (Lu and Lam 2008).

The second production control strategy is called pull or rate driven production. This strategy does not authorize a new construction start unless a ‘void’ is created in the trade network workflow by completion of a job (Gurevich and Sacks 2014). Improvements made by a pull environment are extendable by controlling the number of houses under construction or work-in-process (WIP). Maintaining a constant level of WIP (CONWIP) has positive effects on tangible performance metrics of production house builders (Liu 2010). In fact, this workflow control protocol turns the network of trades into a closed queuing system where unauthorized jobs from outside cannot enter. Despite the wealth of research conducted especially by the lean construction community, reasons behind the superiority of WIP reduction policy and theoretical and practical issues connected to that need more investigation (Schabowicz and Hola 2007).

This chapter quantitatively analyses the tangible performance measures of house builders using two different work levelling methods. Volume house building sector with its data rich environment is a suitable domain for the purpose of this study. First, mathematical models of open and closed queues for individual trade were built and analysed. Because the construction production network are too complex to be solved analytically, in the next step simulation models of the whole trade contractor network were built and run in order to analyse and compare the collected data. Efficiency, coordination and supervisory requirements, and controllability are three areas under investigation in the current study. This chapter suggests that pull (rate driven) production and its workflow levelling protocol of CONWIP can improve both the economic sustainability and efficiency of the house building sector. Improvements in this sector from the use of CONWIP are likely to be generalizable to other sub-sectors of the construction industry due to their similarities.

6.2. Efficiency in the construction production

Underperformance in the construction industry is a problem that is closely related to low productivity levels (Peña-Mora, Han et al. 2008, Skibniewski and Ghosh 2009, Moselhi and Khan 2012). Using an appropriate production control strategy can improve performance metrics in different sectors of the industry, including residential construction. Push and pull are two production control strategies within the interconnected network of trade contractors in house building. Each strategy has unique effects on performance metrics.

One of the builders, coded as builder A in the current study, tries to match the production with sales with the intention of meeting the agreed completion times. In other words, the number of houses under construction (WIP inventory) varies at times based on sales rates, which is represented by the contractors' production output. In this way, WIP acts as a function of output/throughput i.e. $WIP = f(TH)$. This behaviour closely represents push production (Sacks and Goldin 2007).

The other builder, coded as builder B, starts a new house only after a completed house exits production. In fact, the start rate to build new houses varies at times based on the trade network performance and output/throughput rate is a function of WIP inventory, i.e. $TH = f(WIP)$.

This strategy represents pull production, where a new job is pulled into the network upon the completion of one job by the very last specialty trade. Figure 6.1 shows the flow of work in the house building network.

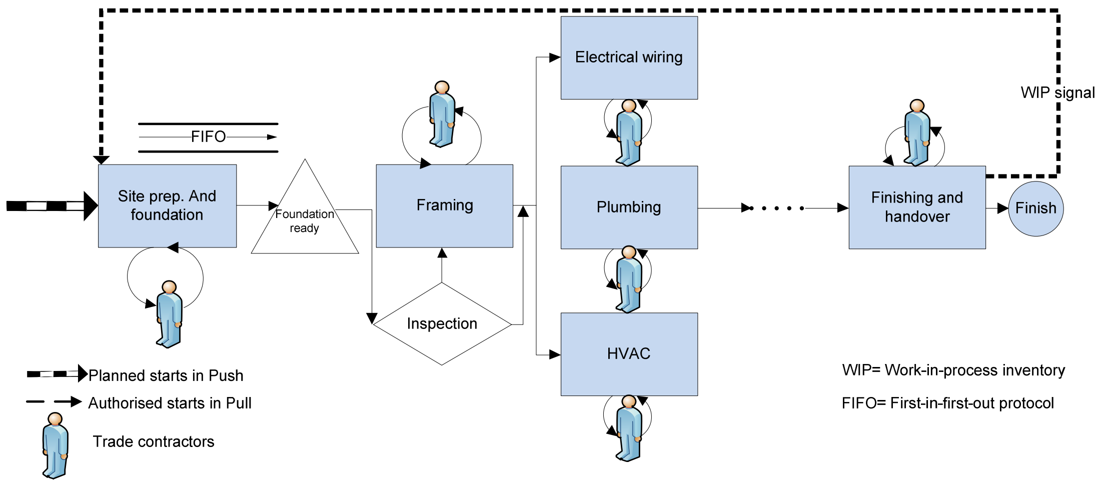


Figure 6.1. Flow of work within the trade network (Push versus pull production)

Figure 6.1 illustrates pull production, which creates a closed queuing network with a production bound, and push construction, which is an open queuing network and jobs can freely enter the network as soon as a sales contract is signed. The stability of workflow in the pull environment enables the network of trade contractors to accommodate an expected level of demand easily. In order to compare the efficiency of push and pull construction, processes of individual trades were first modelled analytically and tangible performance measures were compared quantitatively. Then, simulation models of the whole production network were built and run in order to analyse different what-if scenarios in the real-life construction environment. Care was taken in selecting the two production house builders so that their construction methods are comparable. Behaviours of two production networks in building 1000 detached suburban houses were analysed and compared in the two production networks.

6.2.1. Open and closed queuing networks

As a common practice in the house building industry, more than 100 construction processes are subcontracted to up to 50 trade contractors. Construction methods and process times are similar for specialty trades in both push and pull environments and the output of a trade is always required by the successors in order to perform their tasks. Both production environments are subject to a nonlinear random external demand. The decision variable for the push builder is selecting the start rate of new houses. The trade network in this case acts as an open queuing network where freely fluctuating WIP is observed while the rate of new construction starts is controlled. Queues for houses waiting to be processed by trade contractors can be modelled using queuing theory principles for first-in-first-out (FIFO) queues. According to Kendall's notation (Kendall 1953), the most general form of queue for this case can be represented by G/G/1, in which a Generally distributed demand rate is processed by a trade having a Generally distributed process time, one by one. This queue can realistically represent unsteady-state construction processes because simplifying assumptions such as normal or triangular process times are not required (Walsh, Sawhney et al. 2007).

Adopting a push workflow, the expected number of jobs in the queue to be processes by a trade ($\mathrm{WIP_q}$) can be modelled in a similar approach to Spearman and Zazanis (1992) as Equation (6.1),

$$WIP = f(TH) \xrightarrow{yields} WIP_q = \frac{TH}{1 - TH} \qquad (6.1)$$

In Equation (6.1), TH is the throughput rate of a trade. Understandably, TH is equal to the rate of new construction starts ($\mathrm{r_a}$) when there is not re-entrant flow or rework (Brodetskaia, Sacks et al. 2013). This assumption will be relaxed in the simulation modelling and analysis in the next section of this chapter. Since N trades are interacting in the network, the total work-in-process inventory can be approximated by Equation (6.2),

$$WIP_{total} = \sum_{1}^{N} WIP_q \tag{6.2}$$

In order to model the pull production strategy along with the CONWIP workflow control protocol, a cap should be defined on the inventory of work-in-process (WIP) or number of houses under construction. In this scenario, random external demand is not released to the trade network directly. For example, as suggested by González, Alarcón et al. (2011), a work-in-process buffer can be placed in front of the first trade in order to dampen the effects of demand variability. Consequently, the trade network acts as a closed queuing network where WIP is closely controlled and the rate of new construction starts is observed. In this production setting, throughput is a function of WIP and can be modelled in a similar approach to Arashpour, Wakefield et al. (2013) as Eq. (6.3),

$$TH = f(WIP) = \frac{WIP}{WIP + N - 1} \tag{6.3}$$

In Equation (6.3), N is the number of processors (trade contractors). In order to make a fair comparison between efficiency of the push and pull production, the required work-in-process (WIP) inventory to achieve same levels of throughput rate should be compared in both environments. Towards this aim, WIP is let to build up in the pull network and resultant throughput rate is computed using Equation (6.3). Then, exactly same throughput rates are inserted into Equation (6.1) and (6.2) in order to compute the required WIP inventory in the push production network. The surface chart in Figure 6.2 shows the work-in-process inventory versus achieved throughput rate in the push and pull production environments.

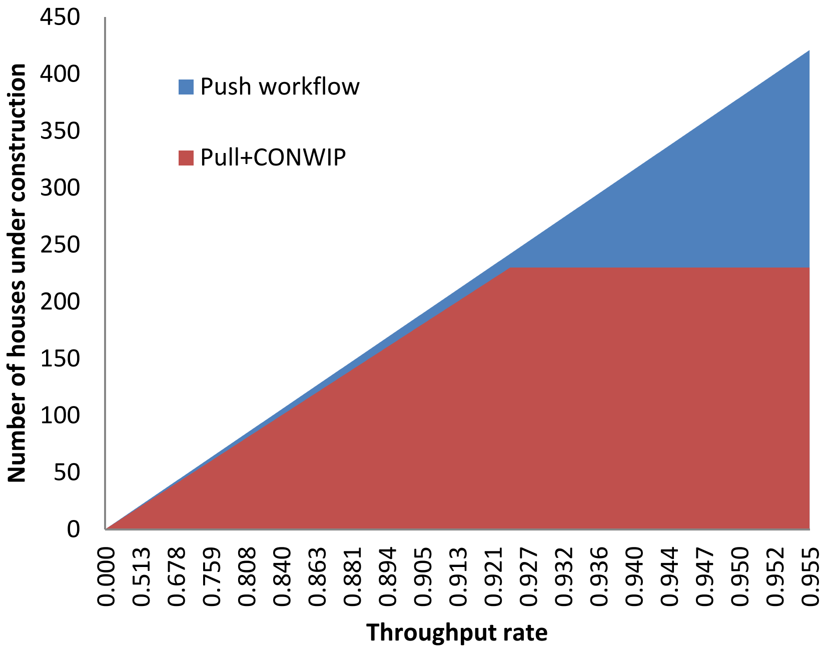


Figure 6.2. Higher levels of work-in-process inventory in the push production than pull production in order to achieve the same throughput rate

As can be seen in Figure 6.2, the pull production network always needs a smaller work-in-process inventory compared to the push production network in order to achieve same rates of throughput and is more efficient. This finding extends those of Tommelein, Riley et al. (1999), confirming that pull is a superior production control strategy in terms of efficiency.

In the next step, computer simulation was used to model production processes of the whole network of trade contractors in order to extend comparisons on performance measures under the two production control strategies.

6.2.2. Simulation experimental framework

The interconnected networks of trade contractors in the construction production are too complex to be solved analytically (AbouRizk, Knowles et al. 2001, Halpin 2010, Lee, Nikolic et al. 2011). Therefore Simulation experiments are useful tools in order to analyse real-life what-if scenarios in the construction production. Stochastic variables of construction production were analysed using ARENA discrete event simulator. Performance metrics of the push and pull production networks were measured by running the simulation experiments for a long production period (16 months).

All simulation models in this chapter and throughout the thesis, involve a strategy that entails completing the construction processes one after the other across all houses under construction. It will be inefficient to build n houses consecutively as it extends the completion time n times longer than that of a single house. Care was taken in order to accommodate nonlinear random demand rates and process times into the model. In order to increase the modelling precision, demand rates and process times were not fit to the theoretical statistical distributions such as exponential or triangular. Instead, ARENA input analyser was used to divide the actual data into groups and calculate the proportion in each group. In this way, accurate empirical distributions were formed for both demand rate and processing times. Average on-site process times of trade contractors were observed and recorded in order to ensure simulation models can realistically represent operations of the two builders. Finally, models were verified and validated by applying modifications recommended by the project and site managers.

The main challenge in modelling the pull production was to characterize the CONWIP strategy and set the desired cap for the number of houses under construction. CONWIP production cannot be precisely modelled using ready-to-use constructs in most simulation systems (AbouRizk, Halpin et al. 2011). A special purpose code in SIMAN simulation language was written preventing the very first trade contractor from starting a new house until a house is completed by the very last trade. Towards this aim the cap for maximum number of jobs under construction was defined using a variable named CONWIP. This variable is decremented when a new job enters the construction network and incremented when a completed job leaves the network. Authorization for starting a new job is only granted if CONWIP variable is greater than zero. Figure 6.3 shows the results of two simulation experiments for the push and pull production control strategies.

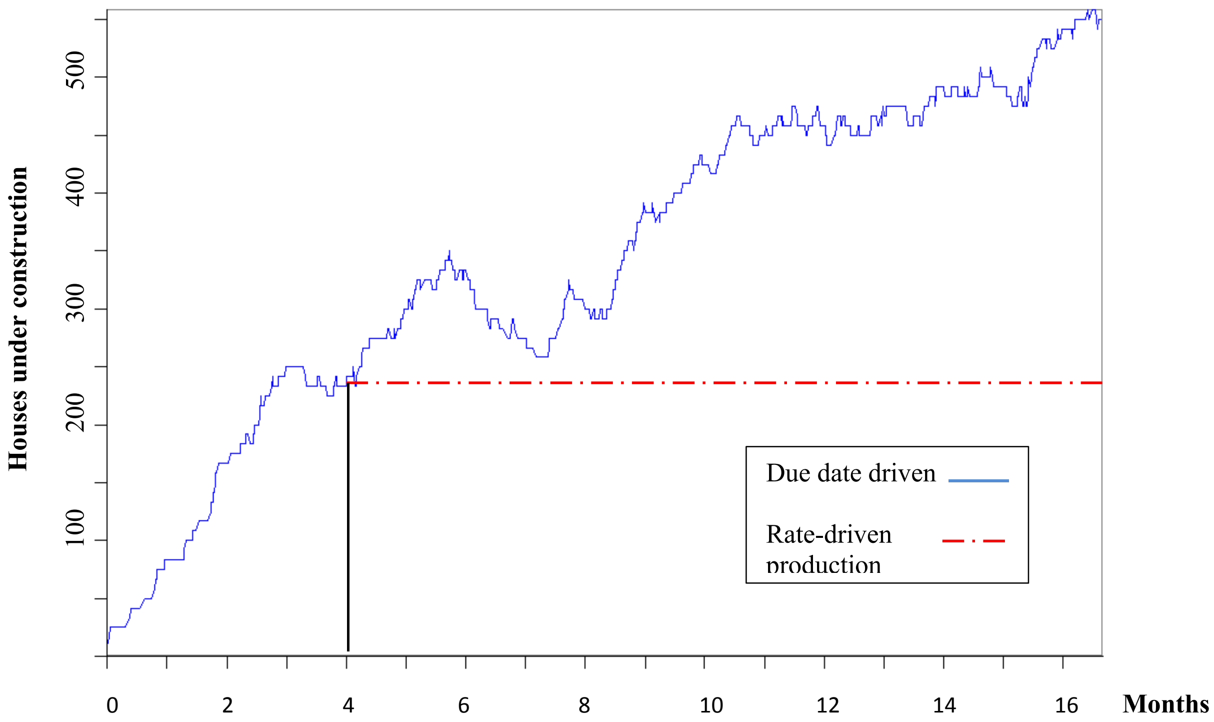


Figure 6.3. Work-in-process (WIP) levels under the two production control strategies

Based on the simulation results and as Figure 6.3 illustrates, the number of houses under construction for both systems grows until two production networks are fully loaded by month 4. Then, pull production manages to set the cap for the number of houses under construction and WIP inventory never grows beyond this level. However, house completions in the push production fall behind the number of starts and WIP inventory continues to grow, reaching a peak of 582 at the end of the simulation period.

This continuous ingrowth of WIP reflects congestion in the push production network and understandably, this congestion inflates the house completion times. Based on the simulation results, number of house completions in the house building network with a cap on WIP level surpasses the network without this workflow control strategy. This fact is evident in the surface chart illustrated in Figure 6.4.

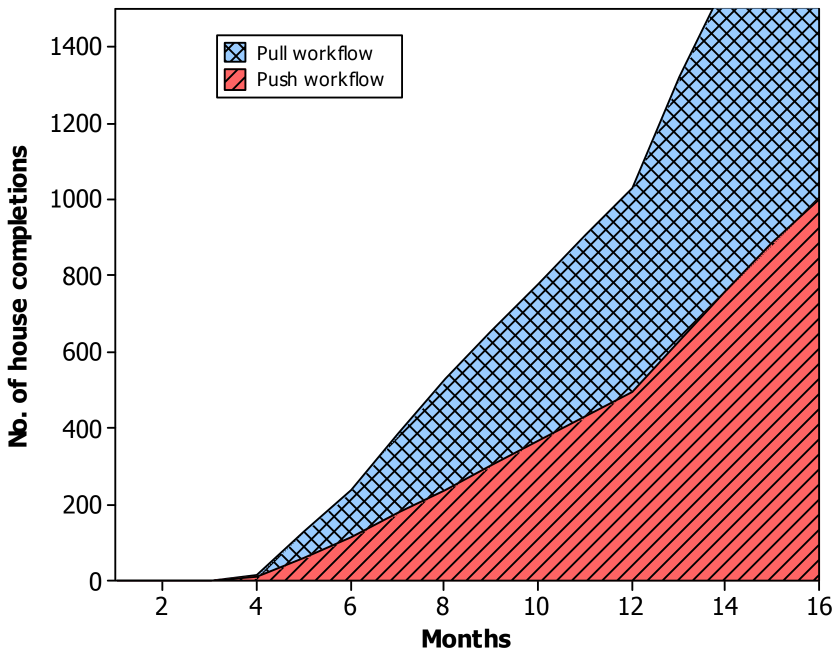


Figure 6.4. Number of house completions (Push production versus pull)

Interestingly, although there are more houses under construction in the push network (Figure 6.3), the output is less than the pull network (Figure 6.4). This proves the fact that the pull production strategy is more efficient than push because pull achieves a higher output level by a smaller level of work-in-process inventory. This is consistent with findings of Gurevich and Sacks (2014), indicating that defining a cap on the work-in-process level can improve the efficiency in the construction production and enable builders to operate their trade contractor network in a more cost-effective way. Furthermore, the simulation results are in line with those obtained by analytical results in the previous section and provide a measure of validation.

6.3. Supervisory and coordination requirements in the push and pull construction production

There is a high level of variability in both processing times and demand rates within the construction and particularly the house building sector. Variability in the construction process is caused by many factors such as accidents on worksites (Del la Garza, Hancher et al. 2000), worker fatigue and illness (Arashpour, Shabanikia et al. 2012), shortage in material supply (Castro-Lacouture, Süer et al. 2009, Hwang, Park et al. 2012), and management-related issues (Cheng, Huang et al. 2013). Furthermore, periods of boom and bust cause variable demand rates for the construction of new houses.

By subcontracting house building processes to specialty trades, the builder will solely be in charge of sales, marketing and construction management. In this case, the major difficulty for the builder is to manage the flow of work or 'hand-offs' among trade contractors (Walsh, Bashford et al. 2004). This complex coordination task is undertaken by building supervisors. In the common practice in the Australian house building, a supervisor usually coordinates construction processes of about 15 houses. This makes supervisors a valuable and highly utilised resource in the production house building (Dalton, Hurley et al. 2013). The objective of this section of the current chapter is to explore possible effects of push and pull production on the supervisor workload.

6.3.1. Analytical model

Both push and pull production environments heavily rely on their building supervisors in order to coordinate the flow of work within the network of trade contractors. In order to develop a special model for comparing the supervisory conditions in the two production environments, the annual target of building 1000 houses was converted it to 83 houses per month and almost three houses per day. Push production exposes the trade network to a random external demand with the mean value of three in order to fulfil the set objective. The builder sets the capacity of resources (trade contractors and building supervisors) so that this average demand can be covered. In particular, enough supervisors need to be hired to coordinate the construction processes. Since demand, as the random variable, is not continuous, it can be represented by a discrete probability distribution such as Poisson ($\text{Demand} \sim \text{Poisson}\ (\lambda = 3)$). In a similar approach to Hopp and Spearman (2008), the probability mass function (PMF) can be used in order to compute the likelihood of having different levels of demand.

$$P(d) = \sum_{1}^{n} \frac{e^{-\lambda}\lambda^{d}}{d!} \qquad (6.4)$$

In Equation (6.4), $P(d)$ is the probability of having a given level of demand and λ is the mean value for the demand rate. Understandably, the expected number of days having a certain demand level can be calculated using Equation (6.5),

$$E(d) = n \times p(d) \qquad (6.5)$$

In Equation (6.5), n is the duration of observation for our set objective, which is 365 working days over 16 calendar months.

It is worth mentioning that sales rates and consequently job arrivals to the network are random. After setting the throughput rate in the push production, there exist periods when supervisors are not busy. The probability of having no demand for constructing new houses is

$$P(d = 0) = e^{-3} \approx 5\,\%$$

Furthermore, the number of idle days for a supervisor can be computed by Equation (6.5), $E\ (d = 0) = 365\, e^{-3} = 18\, days$

During construction boom periods, it is also likely that sales rates are greater than the initial estimation of the push builder. The proportion of time when the push production is not able to keep up with constraints in the capacity of trade contractors and supervisors can be calculated as,

$$P(d > 3) = 1 - P(d \leq 3) = 1 - \sum_{1}^{3} \frac{e^{-\lambda}\lambda^{d}}{d!} = 1 - \left(e^{-3} + \frac{3e^{-3}}{1!} + \frac{9e^{-3}}{2!} + \frac{27e^{-3}}{3!}\right) \approx 35\%$$

This indicates that over a long period of time (127 days over a year) the push production network experiences a slowdown, which is due to trade contractor and supervisor overload. This fact has also been illustrated in Figure 6.5. The shaded area shows the likelihood of having greater demand than the expectation (three houses per day).

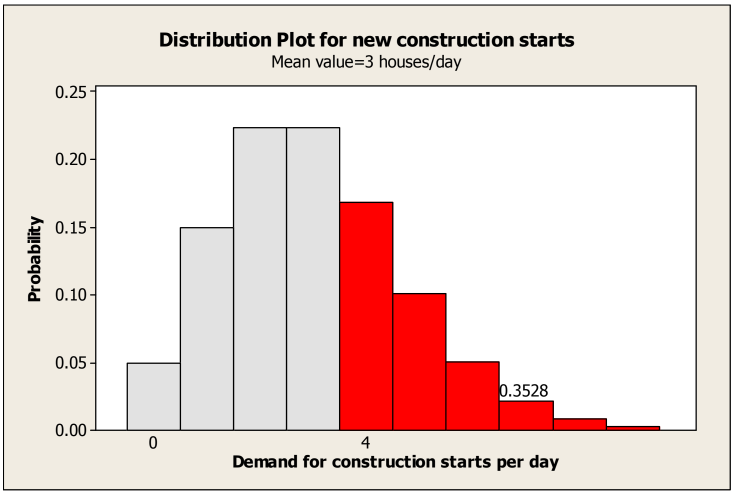


Figure 6.5. Probability distribution plot for the number of new construction starts (Push production)

Overall, these results indicate that push production has difficulties creating a balanced workflow for building supervisors, who experience periods of idleness followed by periods of overload. In other words, supervision and coordination of construction processes is difficult in the push production.

In the next step, simulation experiments are used in order to investigate the behaviour of both push and pull production strategies with regard to building supervision and coordination.

6.3.2. Simulation experiments

The house building processes in the pull production environment are simulated. Frequency statistics are collected in order to observe the daily status of supervisors (idle or busy). In a similar approach to Arashpour, Wakefield et al. (2013), a special purpose code in SIMAN was developed to report on the supervisor status. The simulation models are run for 100 times in order to obtain the desired confidence interval of 99%. Comparison of results for the push and pull production is shown in table 6.1.

Table 6.1. Summary of frequency statistics (status of building supervisors)

	Push production		Pull production	
Supervisor status	**No. of observations**	**Probability**	**No. of observations**	**Probability**
Idleness	18	5%	9	2.5%
Under utilisation	139	38%	139	38%
Balanced utilisation	81	22%	197	54%
Over utilisation	127	35%	20	5.5%
Total	365	100%	365	100%

As can be seen in table 6.1, there are only 9 days over a year when building supervisors are idle in the pull house building network. Additionally, there exist only 20 observations when supervisors experience an excessive workload (supervision of more than 15 houses). More importantly, there was a far more balanced utilisation level for the pull than push building supervisors, 54% versus 22% over the simulation period. These results extend those of Halbach and Halme (2013), indicating that adopting the pull production strategy together with limiting the number of houses under construction can alleviate the variation in the building supervisor workload and increase the coordination level of the construction processes.

6.4. Controllability

In order to compare the controllability of production for the pull and push strategies, two issues of practical implementation and robustness in dealing with control errors are investigated.

6.4.1. Practical implementation

Throughput rate (the number of houses that pass through processes) is set based on the capacity estimations, which can only be done based on detailed evaluation of work efficiency, construction process times, rework and interruptions in the worksites (Hopp and Spearman 2004). Based on an estimation of the true capacity of the trade network in the push house building, throughput is set to the rate of new construction starts $(\mathrm{r_a})$. Upper bound of the throughput rate is limited by the performance of the trade network and is beyond the builder's control. In this way the function of TH can be stated as:

$$TH = \begin{cases} Start\ rate\ (r_a) & if: r_a < capacity \\ Capacity & Otherwise \end{cases} \qquad (6.6)$$

Commonly, an overestimation of the capacity leads the push production strategy to allow for excessive number of construction starts by the trade network and consequently the number of houses under construction will grow rapidly. This is particularly true during construction boom periods when a higher numbers of house completions than normal are desired. This fact makes the implementation of the push production strategy not practical in all cases.

Another issue regarding the practical implementation of the push production is the utilisation rate of trade contractors. Results from running the simulation experiments showed that 50 trade contractors in the push network experience high levels of variation in the flow of work and frequent periods of idleness. This variable workload is difficult and expensive for the trade contractors to accommodate (Bashford, Sawhney et al. 2003). As can be seen in Figure 6.6, utilisation rates (the proportion of time that a trade is busy) fluctuate between 62 and 99 per cent in the push house building network.

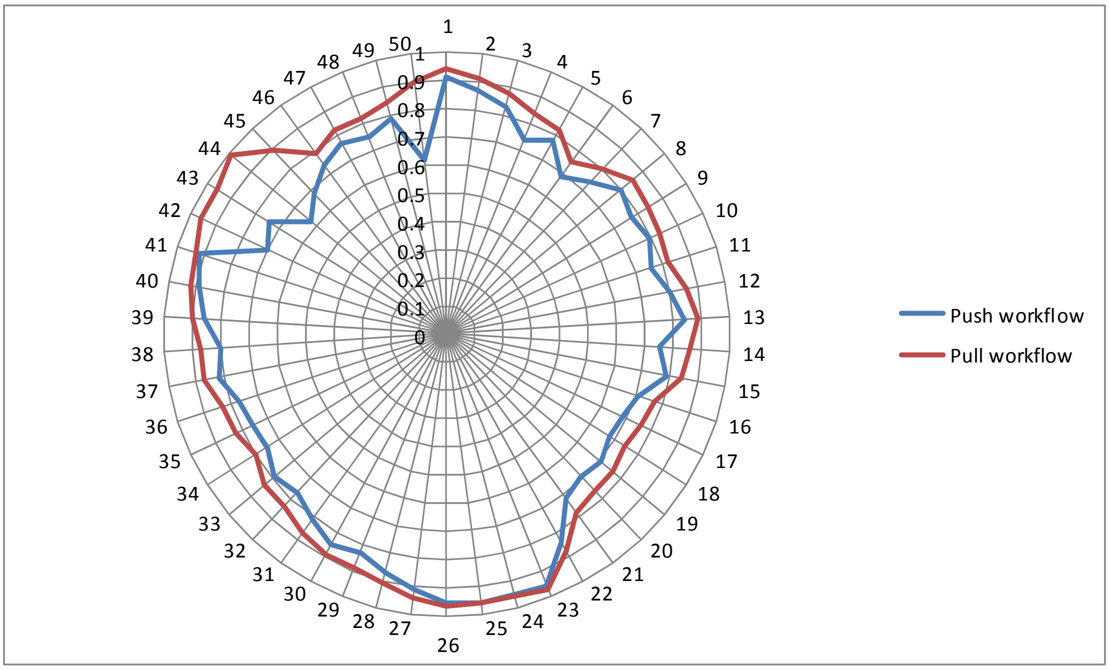


Figure 6.6. Utilisation rates for 50 trade contractors (Simulation results for Push and pull production)

As it is evident in Figure 6.6, in the pull house building network where the number of houses under construction is bounded, trade contractors are more evenly utilised. Here the rates only vary between 80 and 99 per cent and therefore trade contractors can be confident that they will have a continuous flow of work.

While achieving a true capacity estimations and balanced utilisation of trade contractors is difficult in the push production environment, pull production directly observes the number of houses under construction. This is consistent with findings of Ballard (2000) and Koskela, Sacks et al. (2012) indicating that the pull production is a more practical strategy in order to control the flow of work and utilisation within the trade networks.

6.4.2. Robustness

In order to compare the robustness of the two production strategies in dealing with control errors, the optimisation problem of balancing the cost of excessive number of houses under construction and the cost of missed sales opportunities is considered. An excessive work-in-process results in direct and indirect costs such as on-going site establishment costs and overheads. The optimisation problem, attempts to maximise the builder profit by finding a balance between throughput and work-in-process levels. The profit function of the production can be formulated as Equation (6.7),

$$Profit = \alpha_1 \times TH - \alpha_2 \times WIP \qquad (6.7)$$

In Equation (6.7), α_1 is the builder profit for a house and α_2 is the total cost associated with an uncompleted house such as on-going worksite establishment costs and late completion penalties. In order to avoid a biased conclusion in favour of the pull production strategy, profit of a new construction start was assumed to be much higher than costs of having an uncompleted house in the production network (1000x). That is, any house going through the house building processes has the potential to create 1000 units of profit and to incur only one unit of cost. Values of TH and WIP were computed using Equations (6.1) and (6.3) for the push (open queuing network) and pull (closed queuing network) respectively. The internal optimisation tool in MS Excel was used to find the optimal values of TH and WIP that maximises the builder's profit. Pull production profit can reach a peak of \$13.6 M by bounding the work-in-process level to 240 houses. For the push production, the best rate of jobs passing through the processes is three houses per day, yielding a profit of \$13.4 M. Therefore, the maximum profit level for the pull production is slightly (around two per cent) more than the push production. Table 6.2 shows profit values for different TH and WIP levels in the two production environments.

Table 6.2. Profit values for the push and pull production

Push production			Pull production		
TH rate (house/day)	**% of optimal TH**	**Profit**	**WIP Inventory**	**% of optimal WIP**	**Profit**
0	0	0	0	0	0
1.5	50	10.0 M	120	50	11.4 M
3 (optimal)	100	13.4 M	240 (optimal)	100	13.6 M
4.5	150	-1.0 M	360	150	11.5 M
6	200	-7.9 M	480	200	6.6 M
7.5	250	-53.3M	600	250	0

As can be seen in Table 6.2, profit values are not very sensitive to WIP levels in the pull production and vary smoothly for WIP levels, even far from the optimal. In contrast, there is a sharp fall in the push production profit for non-optimal TH rates. Periods of construction boom and tendency to build more houses generally results in excessive number of construction starts in the push environment. As table 6.2 shows, having 50 per cent more TH than the optimum rate results in a loss for the push production. However, the pull production continues earning profits until reaching 250 per cent of the optimum number of houses under construction (600 houses).

The results show that limiting the number of houses under construction is a more observable control parameter than setting the throughput rate. This extends findings of Palaniappan, Sawhney et al. (2007) confirming that pull production is a more robust strategy than push production in terms of dealing with control errors.

6.5. Chapter summary

Previous research has documented the implications of pull production in construction. In particular, production control strategies such as controlling the work-in-process (CONWIP) have been at the centre of attention (Bashford, Sawhney et al. 2003, Koskela, Sacks et al. 2012). This chapter analysed the theoretical and practical reasons behind efficiency improvements in pull production together with the CONWIP workflow control protocol. Towards this end, both push (due date driven) and pull (rate driven) production in the house building sector were analysed and compared.

Based on the results, adopting the pull production control strategy along with maintaining a constant level of work-in-process can significantly improve tangible performance metrics in volume house building. The findings extend those of Sacks and Goldin (2007) and Koskela (2000), confirming that direct control of the work-in-process inventory is more feasible than indirect control of throughput and capacity estimations in the push environment. Furthermore, results of analytical models and simulation experiments produced several key observations about the superiority of pull production in the real world construction, such as robustness against errors in determining the optimum number of houses under construction. In fact, optimism in estimating production capacity and the desire to yield as much throughput as possible to maximise profit are making push production prone to errors in the control parameters. That is, overestimating the capacity of the trade contractors' network results in more construction starts and can lead to a loss of money and therefore cash flow problems for the builders.

6.6. Chapter contributions and future research opportunity

The research reported in this chapter builds up on the current body of knowledge by developing an in-depth insight into the pull and push production control strategies. The results have considerable potential to improve construction production management particularly in three key aspects of efficiency, supervision and controllability. This research is also generalizable to other sub-sectors of the construction industry. Future research should investigate effects of pull and push production control strategies on performance, cost-effectiveness and flexibility in those sub-sectors of construction.

7. Chapter Seven – Variability buffering in the FULFIL system of production control

7.1. Introduction

In chapter six, pull production together with the CONWIP workflow control protocol were proposed as the main variability reduction tools in the FULFIL system. It was found that these tools can significantly improve the productivity and efficiency. The variability reduction tools also make construction production systems more controllable and robust against control errors. Variability in processes and demand, however, cannot be totally eliminated. There should be a mechanism in a comprehensive control system to buffer against the remaining variability in production networks. Chapter seven proposes a tailored framework for variability buffering that is used in the FULFIL production control system.

Construction sites are dynamic environments due to the influence of variables such as changes in design and processes, unsteady demand, and unavailability of trades. These variables adversely affect productivity and can cause unstable workflows in the network of trade contractors. Previous chapters of this thesis have shown the effectiveness of ‘pull’ production or ‘rate driven’ construction. Pull systems authorise start of construction when a ‘void’ is created by a trade in the network as a result of completing a job. However, the problem with pull systems is that completion dates are not explicitly considered and therefore additional mechanisms are required to ensure the due date integrity. On this basis, the aim of this chapter is to improve the coordination between output and demand by using optimal-sized capacity buffers.

Production in dynamic environments such as construction sites are prone to variability caused by external factors such as unsteady demand and internal factors such as unavailability of resources. This high level of variability results in late completion, decreased output, and lost revenue opportunity for contractors (Lee and Diekmann 2011, Chanmeka, Thomas et al. 2012). Stabilising the workflow in the trade contractor network coordinates the production output and demand and results in a synchronised production (Love, Zhou et al. 2013). Prior work in the construction literature has focused on designing and implementing pull production systems in order to stabilise the workflow in construction production systems (Im, Han et al. 2009, Gurevich and Sacks 2014).

The main workflow control mechanism in pull production or rate driven construction is to maintain a constant work-in-process (CONWIP) level for the trade network over the production period (Spearman and Zazanis 1992, Liu 2010). The CONWIP protocol enables trade contractors to plan ahead in order to accommodate the external demand. Since due dates are not explicitly considered in pull systems, a second control mechanism is also required. A capacity buffer or under capacity scheduled system can ensure the due date integrity in the pull production (Hopp and Spearman 2008). However, as stated by González, Alarcón et al. (2011), research on capacity buffers and their effects on tangible performance measures in the construction literature is sparse.

This chapter aims to improve the coordination of demand and output of construction using an optimal capacity buffer. In order to achieve this, production data of two volume house builders in Melbourne and Brisbane, Australia were collected. Then, time series analysis was used to analyse the data and find the gross production capacity for the next production period. In the next step, capacity and cost optimisations were conducted in order to find the optimal capacity buffer that strikes the balance between late completions and lost revenue opportunity. Finally, results of the mathematical modelling were linked to a discrete event simulation engine where 1200 simulation experiments were designed and run in order to analyse production scenarios in the real-life construction. The findings of this chapter clearly show that loading the network of trade contractors to full capacity is not always the most profitable policy. In fact, workflow in the network of trade contractors can be stabilised using optimal-sized capacity buffers. Furthermore, the tested and validated framework could be adopted by house builders in order to maximise the profit and avoid late completion costs.

7.2. Literature review

The prevalence of schedule overruns in the house building industry is high (Kim 2009). As the common practice in the house building industry, risk of late completion is transferred to trade contractors by linking remunerations to the completion of processes (Walsh, Bashford et al. 2004). Any remaining risk is then transferred to homebuyers by eliminating/minimising late completion penalties in the house building contractual terms. Manufacturing industry, however, has dealt with schedule overruns in a more robust way.

Initiatives such as the Toyota Production System (TPS) tend to continually improve the production environment (Amasaka 2002, Lander and Liker 2007). Furthermore, workflow control protocols such as 'Kanban' attempt to stabilise the workflow in the plant as much as possible and reduce the probability of schedule overruns (Kogut 2000). However, variability in the production will always result in late completions regardless of how much the production environment has been improved. This fact highlights the need for a capacity buffer or under capacity scheduling.

In the following sections, two production control approaches in the volume house building sector are introduced.

7.2.1. Due date driven construction

In the traditional construction management approach, building new homes are initiated by signing new sales contracts. In this way, due date integrity can only be achieved when demand is not excessive and subcontractors are able to catch up with that (Cheah and Chew 2005, Han 2008). However, during construction boom periods, when demand exceeds supply, pushing the interconnected network of trade to start new houses, creates numerous unfinished jobs and congestion in the workflow. In other words, trade contractors, as the main labour resource in the production network, will be fully utilised and therefore unfinished jobs queue up, waiting for a resource to become available (Damrianant and Wakefield 2000).

Another problem for achieving due date integrity in push construction production is caused by the ubiquity of variability and uncertainty in construction worksites. There are many sources of variability in construction sites such as quality problems and rework (Fayek, Dissanayake et al. 2004, Hegazy and Menesi 2012, Hazini, Dehghan et al. 2013), changes in design and processes (Thomas, Lee et al. 2008), labour productivity (Sonmez 2007, Jarkas 2010, Arashpour, Shabanikia et al. 2012, Dai and Goodrum 2012), contractor's cash flow (Son, Mack et al. 2006, Zayed and Nosair 2006) and undesirable weather conditions (Moselhi, Gong et al. 1997, Shahin, Abourizk et al. 2014). Variability prevents a stable and smooth workflow in the construction network and downgrades the performance measures such as completion time and throughput (Jongeling, Kim et al. 2008, Hewage, Gannoruwa et al. 2011).

7.2.2. Rate driven construction

In order to rectify the problems in the due date driven production, stability of workflow has become the main focus in the rate driven construction. This approach authorises new constructions only when a 'void' in the workflow becomes available upon the completion of a house (Bashford, Walsh et al. 2005). In this way, the house production network does not become congested as new starts are only authorised upon the availability of resources. This workflow management strategy, which is very similar to pull production in the manufacturing industry, has been successfully tested in large residential projects (Bashford, Sawhney et al. 2003). Using a capacity buffer in dealing with unscheduled contingencies enables rate driven construction to effectively address variability in construction sites (Arashpour, Wakefield et al. 2013).

Rate driven construction offers significant benefits over due date driven approaches. To mention some benefits, rate driven production systems are: more efficient (Sacks, Koskela et al. 2010), more robust to control errors (Ballard and Koskela 2009), and more supportive of improving quality (Sawhney, Walsh et al. 2009). Furthermore, setting an optimal production level (quota) with an appropriately sized capacity buffer can result in coordination between output and demand (Hopp and Spearman 2008). Understandably, the probability of missing the quota should be reasonably low to avoid frequent late completions. Consequently, trade-offs need to be made in order to set an optimal production level because high production levels increase the risk of schedule overruns and resulting costs of a late completion. On the other hand, low production levels or under capacity scheduling result in a profit loss because of missing sales opportunities. This chapter proposes a framework that realises this trade-off and sets an optimal capacity buffer to improve workflow stability.

7.3. Research method

7.3.1. Theoretical basis of the framework

The goal of the framework is to find an optimal capacity buffer that maximises the builder profit by stabilising the workflow and minimising late completion costs. Although the theoretical basis of the proposed framework to achieve this purpose has been partly adopted from quota setting research in the manufacturing industry (Duenyas, Hopp et al. 1997, Qu and Wang 2006), it has been customised in order to reflect realities in the construction production. High levels of variability, on-going site establishment costs, late completion penalties and different what-if scenarios in construction are among the factors considered in structuring the framework. Figure 7.1 illustrates the proposed framework in this chapter.

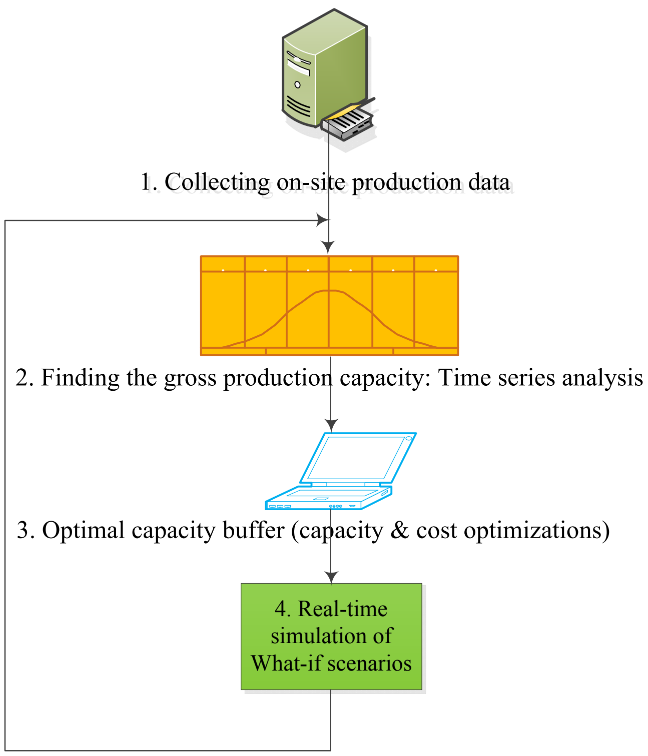


Figure 7.1. Framework for improving the workflow stability (using optimal capacity buffers)

7.3.2. Stages of the framework

As can be seen in Figure 7.1, the proposed framework is made of the following stages.

Stage 1- Collecting the production data: Important information reflecting the production network capacity should be recorded. Some data reflect the production rate such as number of houses started and completed per month. Furthermore, degree of the workflow stability is reflected by the standard deviation of time between completions. These data points are used in the computations in next stages of the framework.

Stage 2- Gross production capacity forecasting: Having collected the actual production data, it is analysed using time series predictive models. Since factors affecting the construction demand, and consequently production, such as house design, builder's own marketing strategy and market competition are persistent over time, past data can be indicative of future and time series can serve as a suitable tool for finding a gross production capacity (Choy and Ruwanpura 2006, Dissanayake and Fayek 2008, Lee, Fung et al. 2013). This gross production capacity can facilitate management of the construction workflow in the following stages.

Stage 3- Setting an optimal capacity buffer: This part of the framework addresses minimising the probability of late completions by setting a properly sized capacity buffer. Towards this aim, mathematical models (Equations (7.4) to (7.6)) are used to formally state the problem of finding the optimal production level and capacity buffer in the construction production. In the third stage of the framework, two scenarios are analysed. In the first scenario, there is no significant late completion cost for the builder and the major concern is the capacity of the trade contractor network. In the second scenario, late completion costs are significant. Therefore, both capacity and cost optimisations are conducted in order to find the optimal size of the capacity buffer.

Stage 4- Real time simulation of what-if scenarios: The results of optimisation in stage 3 are linked to a discrete event simulation engine in order to analyse different what-if scenarios in the construction production. Simulation results are recorded in an output data file and can be updated upon the emergence of new production scenarios.

In terms of applying the framework to a construction setting, results of the framework can be automatically used for a future production level setting. Actual on-site progress can be used for reconsidering the size of the capacity buffer in a future production period. Iterative processes of the framework can be repeated in short time intervals in order to have a more accurate production planning.

7.4. Results

7.4.1. Stage 1- Collecting the production data

Based on the collected production data, number of house completions between January 2011 and December 2013 is illustrated in Figure 7.2. Availability of data over long periods of time increases the precision and reliability of predictive models (Blair, Lye et al. 1993, Kim 2013).

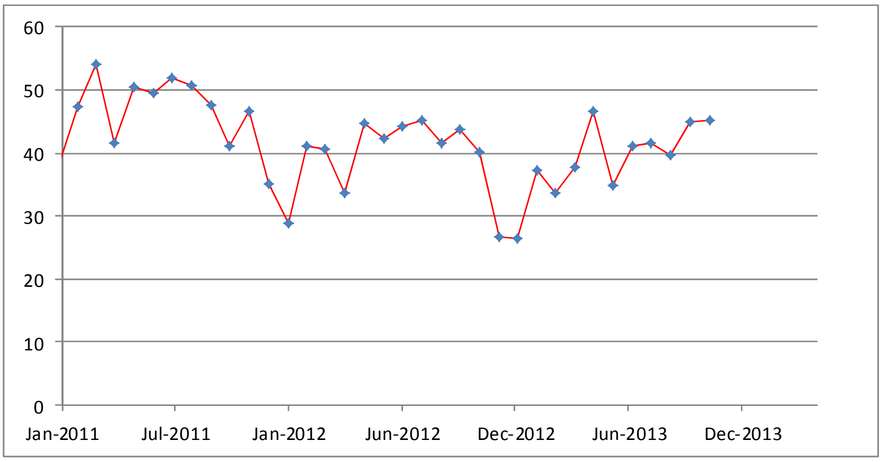


Figure 7.2. Number of house completions over 36 months

As can be seen in Figure 7.2., number of monthly completions fluctuates between 26 and 54 houses.

The first step towards deployment of optimized capacity buffers is to collect important information reflecting the capacity of construction network. The information is then used to estimate a gross production capacity. When prior production data is not available – as is the case with a new builder or non-traditional construction – a rough estimation of the production capacity can initiate the framework calculations. This estimation can be based on expert ideas (e.g. project manager) or industry standards in similar projects. Due to iterative nature of the proposed framework for finding optimal-sized capacity buffers, the initial estimation does not cause significant error in the long-term.

7.4.2. Stage 2- Finding the gross production capacity of the trade contractor network

In order to predict the gross production capacity of the trade network in the next production period, four time series forecasting models were used to analyse the data: moving average, single exponential smoothing, double exponential smoothing and Winter's method. These models predict the gross production capacity by using smoothing constants, α, β and γ. Care was taken in order to automate different stages of the framework and minimise the required user interference. For example, Solver, the internal optimisation tool in MS Excel, was used to compute the optimum values for smoothing constants. In order to compare forecasting models, three quantitative measures were used: mean absolute percentage error (MAPE), mean absolute deviation (MAD), and mean square deviation (MSD). These accuracy measures were computed using Equations (7.1) to (7.3),

$$MAPE = \frac{\sum_{t=1}^{n} \left| (x_t - \hat{x}_{t)} / x_t \right|}{n} \times 100 \qquad (7.1)$$

$$MAD = \frac{\sum_{t=1}^{n} |x_t - \hat{x}_t|}{n} \qquad (7.2)$$

$$MSD = \frac{\sum_{t=1}^{n} [x_t - \hat{x}_t]^2}{n} \qquad (7.3)$$

In Equations (7.1) to (7.3), x_t is the actual number of monthly completions, $\hat{x}_t$ is the gross capacity forecast and n is the number of observations, which is 36 (months). Each of the accuracy measures computes a numerical score for the difference between actual and fitted values. Smaller values of accuracy measures show a greater forecasting precision (Abdelhamid and Everett 1999, Wong, Chan et al. 2011). Table 7.1 presents the accuracy measures for the four predictive models.

Table 7.1. Three quantitative measures for evaluating the accuracy of gross capacity forecasting

Accuracy measure	**Moving average**	**Single exponential smoothing**	**Double exponential smoothing**	**Winters method**
MAPE	14.85	13.40	13.76	6.52
MAD	5.01	5.05	5.17	2.62
MSD	45.49	38.53	41.97	10.35

Comparing the measures of effectiveness in table 7.1 shows that the Winters method has the smallest accuracy measure values and therefore is the most accurate model to find the gross production capacity of the trade contractor network. This is because the Winters method captures seasonality and does not overshoot or undershoot the actual production data (Suhartono and Lee 2011). Using the Winters forecasting model, Figure 7.3 shows the results of gross capacity analysis over the next production period.

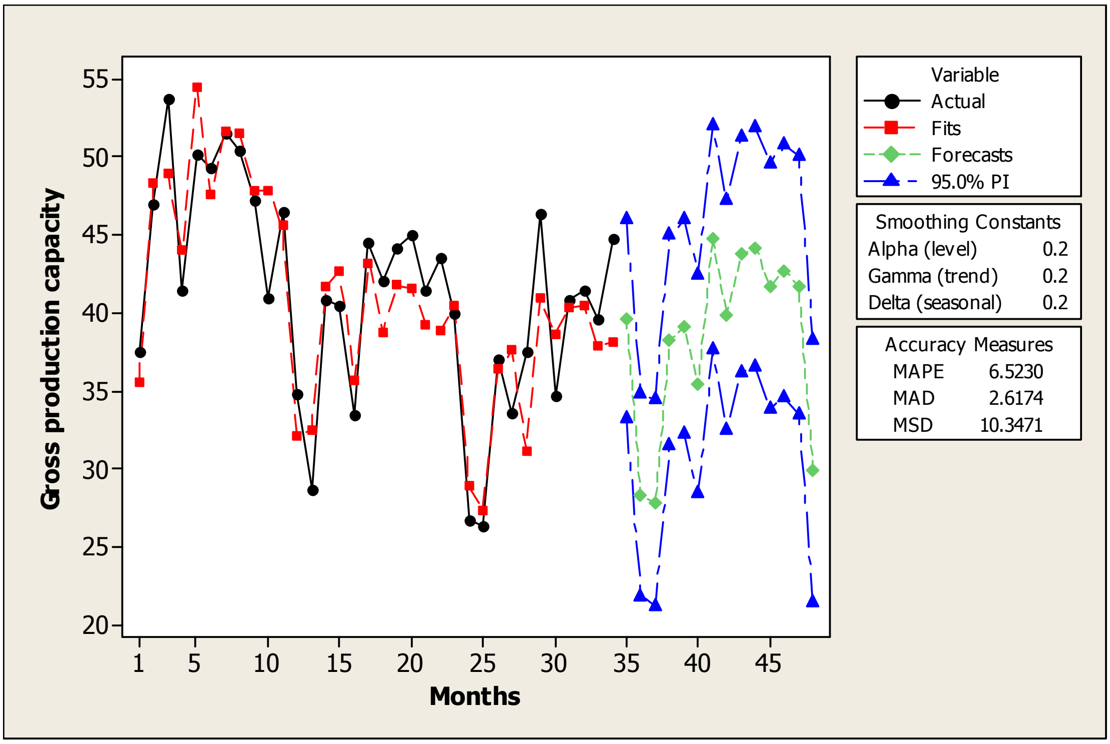


Figure 7.3. Gross production capacity of the trade contractor network (house/month)

A reasonably accurate capacity forecast based on the actual production data enables builders to plan ahead and find the most cost-effective way to operate their production network. For example, the gross production capacity forecast for the coming month is equal to 42 houses (see Figure 7.3) and therefore the network of trades, as the main labour resource, is organised so that this level of monthly production can be achieved. That is, the monthly productivity mean or gross production capacity of the trade network is set to $\mu = 42$.

However, actual number of house completions is often less than the gross capacity of the trade network because of the usual contingencies such as unavailability of trade contractors, quality problems and rework, and inclement weather conditions. Actual house completion times are inflated dependent on the presence of variability/uncertainty and so is the risk of undergoing extra costs such as on-going site establishment costs and late completion penalties (Salazar-Kish 2001).

In order to minimise the probability of late completions and stabilise the workflow within the trade contractor network, an optimal-sized capacity buffer is required. In the next sections, two different analytical models are developed to find the optimal size of the capacity buffer in two production scenarios. In the first scenario, which is generally the case in Australia, late completion costs are not significant for the builder and decision on the size of the capacity buffer is based on the trade network capacity. In the second scenario, late completion penalties and on-going site establishment costs are considerable and both capacity and cost optimisations are conducted.

7.4.3a. Stage 3- Setting the capacity buffer based on the capacity of the trade contractor network (scenario 1)

In order to find an optimal capacity buffer, this scenario assumes that late completion costs are not significant and decision making is based on the capacity of the trade network. If the agreed completion date is not met, the builder undergoes extra costs associated with a late completion. In this scenario, setting the work-in-process (WIP) level is the most important control measure. In addition, another control measure is also required in order to buffer variability and coordinate the construction output with due dates (Hsie, Chang et al. 2009, Arashpour, Wakefield et al. 2013).

The capacity of a house building network depends on both mean and standard deviation of production. Level of workflow variability in the interconnected network of trades can be reflected by standard deviation of time between completions (Koskela, Sacks et al. 2012). For instance, two builders may have identical productivity means (μ) but standard deviation (σ) is greater in the production network of the first builder. Understandably, the second builder needs a smaller capacity buffer in order to accommodate a similar demand level. In other words, the production predictability of the second builder is greater than the first one. If the production can be approximated by the normal distribution and the gross monthly capacity mean is estimated to be 42 houses (based on predictions in stage 2), then the production curve of the trade network can be illustrated by Figure 7.4.

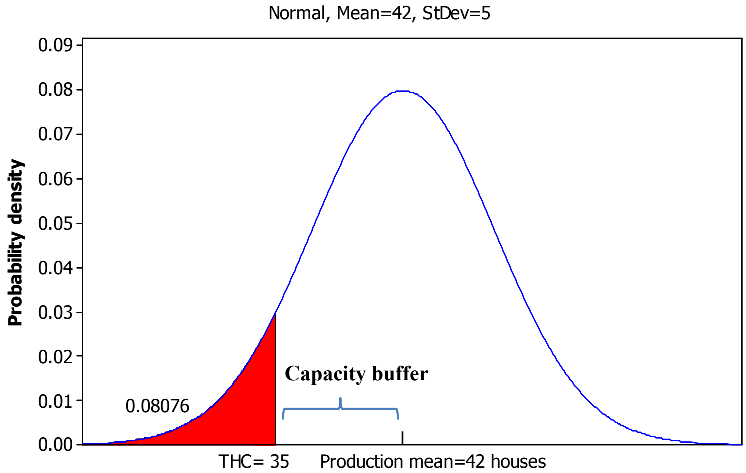


Figure 7.4. Capacity buffer in the production house building

As can be seen in Figure 7.4, the network of trade contractors has the gross capacity of completing 42 houses per month. As the first control measure in a rate driven (pull) environment, the work-in-process (WIP) level should be observed so that no more than 42 houses are started each month. Furthermore, the second control measure in form of a capacity buffer ensures that start and finish of houses are coordinated and production synchronisation is maintained. For example, a capacity buffer of seven houses in Figure 7.4, coordinates the number of starts and completions in 92% of time. In other words, the probability of missing a target house completion (THC) or quota of 35 is only 8% and the builder achieves a service level (SL) of 92%. Production curves of builders with lower variability in production have thinner tails. Therefore, probability of missing the target house completion will be less. Assuming a normal distribution for the house building processes, the problem of finding an optimal capacity buffer can be formulated as Equation (7.4),

$$\Phi\left(\frac{THC - \mu}{\sigma}\right) = 1 - SL \tag{7.4}$$

In Equation (7.4), $\Phi(.)$ is the cumulative density function (CDF) of production, THC is the target house completion and SL is the desired service level for the house builder (production reliability). The capacity buffer is equal to $THC - \mu$. The capacity buffer adopts negative values as it downsizes the gross production capacity by a safety factor. For example, suppose that the trade contractor network has the gross weekly production capacity of 11 houses with a standard deviation of two. If the desired service level is 85%, the model expressed by Equation (7.4) will return a target house completion of $THC = 9$. Therefore, the capacity buffer is equal to (-2) houses or 18% of the gross production capacity. In other words, by adopting this capacity buffer, the builder will be able to coordinate dates of house start and finish and synchronise production in 85% of time. It is worth mentioning that all computations can be automated using built-in functions in standard statistical packages or MS Excel. For example, in order to return the standard normal distribution, $NORM.S.DIST(.)$ in Excel 2010 and $PHI(.)$ function in Excel 2013 were used.

Table 7.2 presents THC values for different service levels of 85, 90 and 95%. The size of the capacity buffer is equal to $THC - \mu$ in each construction production scenario.

Table 7.2. Capacity buffer in 18 production scenarios with different service levels

σ	1									2								
μ	9			10			11			9			10			11		
$SL\%$	85	90	95	85	90	95	85	90	95	85	90	95	85	90	95	85	90	95
THC	8.0	7.6	7.4	8.9	8.7	8.4	10.0	9.7	9.5	6.9	6.4	5.6	7.9	7.5	6.7	9.0	8.4	7.7

As can be seen in table 7.2, greater values of gross production capacity return higher THC. However, THC is decreased by either increasing the standard deviation of time between completions or the desired service level. These results are in line with those of Sacks, Radosavljevic et al. (2010) and Han, Hong et al. (2011), highlighting the importance of variability buffering in construction processes, especially when higher service levels are desired

The model expressed by Equation (7.4) can be used when capacity of the trade network is the main independent variable affecting the construction production. However, upon the existence of significant late completion costs, this factor should also enter the size setting process of the capacity buffer. In such situations, builders need to consider the trade-off between a bigger capacity buffer, which imposes the lost revenue opportunity, and a smaller buffer, which increases the late completion costs. The model developed in the next section, realises this trade-off and optimises the size of the capacity buffer accordingly.

7.4.3b. Stage 3- Setting the optimal capacity buffer based on both the capacity of trade network and costs of a late completion (scenario 2)

In order to find an optimal capacity buffer in this scenario, major costs associated to a late completion have been considered and decision making is based on both capacity of the trade network and these costs.

In order to develop a specific model for setting the optimal capacity buffer, time series analysis in stage two computed the gross production capacity in the coming month that is equal to 42 houses or almost 10 houses per week. If agreed completion dates are not met, builders have to pay extra costs of on-going site establishment and late completion penalties, if stated in the house building contract. Consider the total cost of late completion (C_{LC}) be \$300 per week for each house. So for a builder with 10 houses under construction, C_{LC} = \$3000 for a week of delay in completion.

Let the net profit of the builder earned per house be (e) and the total expected earnings (net revenue minus expected C_{LC}) be denoted by (E). In this way, the problem of finding an optimal capacity buffer can be formulated as Equation (7.5),

$$\max_{THC} E = e \times THC - C_{LC} \times p\ (late\ completion) \qquad (7.5)$$

In Equation (6.5), (p) is the probability of having a late completion and size of the capacity buffer is equal to $THC - \mu$. The optimisation problem is to find an optimal buffer that strikes the economic balance. While increasing buffer size affects the objective function by causing lost sales, decreasing buffer size affects the objective function by increasing probability of late completions and associated costs. Assuming a normal distribution for production with a mean (μ) and a standard deviation (σ), the capacity buffer can be expressed as $THC - \mu = -m \times \sigma$. Now the decision variable becomes m and we need to find out how many standard deviations below μ the capacity buffer should cover. In a similar approach to Hopp, Spearman et al. (1993), the problem was formulated as Equation (7.6),

$$\max_{THC} E = e(\mu - m\sigma) - C_{LC} \times p\,[1 - \Phi(m)] \qquad (7.6)$$

In Equation (7.6), $\Phi(.)$ is the cumulative distribution function of production. A unique solution to Equation (7.6) was yielded by differentiating the objective and setting it equal to zero.

$$m^* = \left[2\ln\left(\frac{C_{LC}}{\sqrt{2\pi}\sigma e}\right)\right]^{1/2} \qquad (7.7)$$

The optimal value of m in Equation (7.7) is used to compute the optimal capacity buffer size,

$$THC^* - \mu = -m^* \times \sigma \qquad (7.8)$$

Equation (7.8) shows that both gross capacity mean and standard deviation of time between completions affect the size of capacity buffer. Table 7.3 shows how these two variables change the house completion target (THC) and consequently the capacity buffer size. As stated earlier, all computations were automated using built-in functions and the internal optimisation tool in MS Excel.

Table 7.3. Capacity buffer in 12 production scenarios with different late completion costs

C_{LC}	350						400					
σ	1			2			1			2		
μ	9	10	11	9	10	11	9	10	11	9	10	11
THC	7.6	8.7	9.6	7.4	8.5	9.4	7.5	8.4	9.5	7.1	8.0	9.1

Results in table 7.3 can be used to find the optimal capacity buffer. For example, in a case where the trade contractor network has a gross production capacity of 10 houses per week with a standard deviation of one house and weekly cost of late completion is $400, the model returns a THC equal to 8.4. This capacity is equal to 16% of the gross production capacity of the trade network.

Results of the optimisation model show that increasing the standard deviation of production and costs of late completion C_{LC} decreases the target house completion or production quota. This is consistent with findings of Yoon and Ventura (2002), Georgy (2008) and Ko and Wang (2010), indicating the impact of production variables on the size of the capacity buffer.

7.4.4. Stage 4- Real-time simulation of what-if scenarios

Data obtained in previous studies has shown that variability in the processes of trade contractors results in a reduced throughput, low resource utilisation levels and a higher allocation of overheads (Tommelein, Riley et al. 1999, Aram, Eastman et al. 2013). Construction sites are dynamic environments and production is subject to numerous variables (Cheng and Feng 2003, East, Martinez et al. 2009, González and Echaveguren 2012). In order to relax the assumptions made in the analytical modelling, simulation experiments were designed and run as construction projects are not appropriate laboratories for multiple replications in a quantitative study (Brodetskaia, Sacks et al. 2013). A total of 1200 simulation experiments were designed by combining five gross production capacities, six standard deviations of time between completions, four service levels and 10 values for late completion costs. Input variables to simulation models were automatically read from an excel spread sheet that contained the collected data. The project workflow was simulated using the ARENA discrete-event simulation system.

7.5. Analysis

7.5.1. Impacts of service level on the size of the capacity buffer

Based on the simulation results, Figure 7.5 shows increasing the desired service level (SL) inflates the size of capacity buffer nonlinearly and consequently squeezes the target house completion (THC).

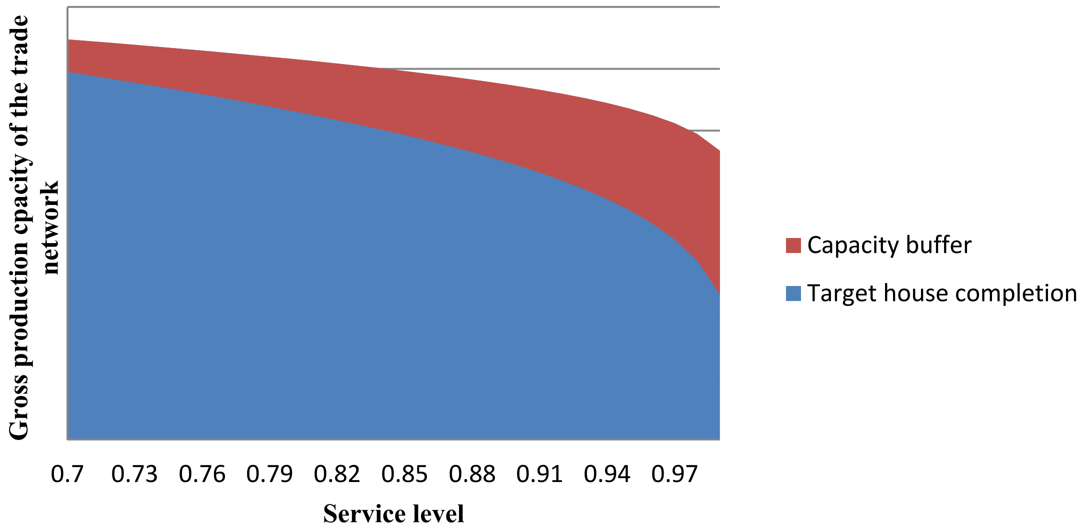


Figure 7.5. Optimal size of the safety capacity buffer in simulation experiments (enforcing a growing service level)

As Figure 7.5 reveals, increasing the service level decreases the level of target house completion (THC) in a nonlinear trend. That is, if the builder tends to have reliable production and achieve on time completions, a conservative THC level should be maintained. This is consistent with the optimisation results in the previous section (table 7.2) and provides a measure of validation. Furthermore, it extends finding of Gokpinar, Hopp et al. (2010) and Arashpour, Wakefield et al. (2013), indicating that loading operations to the full capacity is not necessarily the best production strategy and a decent-sized capacity buffer will help both homebuilders by avoiding late completion costs and homebuyers by shortening the preoccupancy period.

7.5.2. Impacts of the gross production capacity and workflow stability on the size of the capacity buffer

Optimisation models in the previous stage of the framework revealed that size of the capacity buffer is dependent on the gross production mean and standard deviation of time between completions. In a controlled simulation experiment, the productivity mean was relaxed to fluctuate between 400 and 600 houses per year while the standard deviation of time between completions was fixed. Results of running the simulation experiment have been illustrated in Figure 7.6.

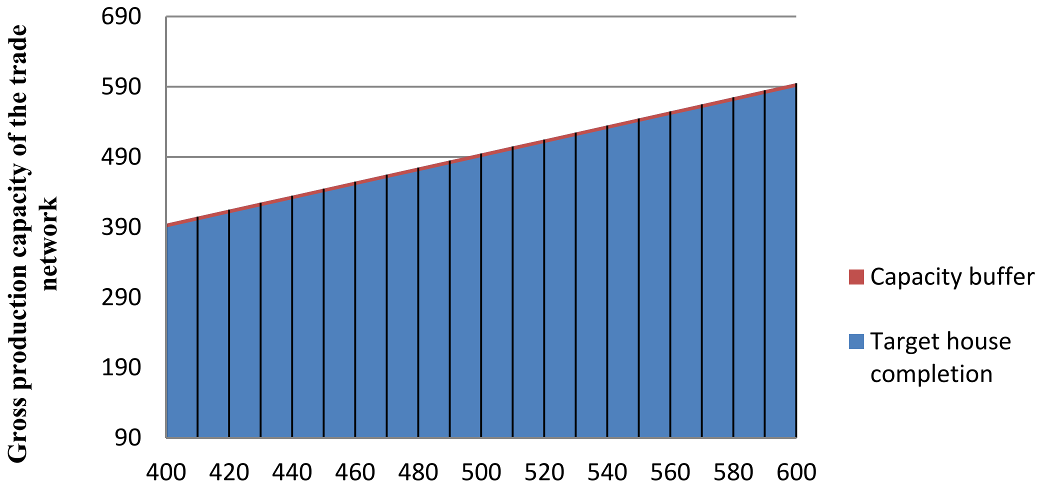


Figure 7.6. Target house completion and capacity buffer (controlled for production variability)

As can be seen in Figure 7.6, increasing the gross production capacity results in a growing level of target house completion ($\boldsymbol{THC}$). However, it is controlling the standard deviation of time between completions that keeps the size of the capacity buffer constant. It is worth mentioning that having a stable workflow by fully controlling the variability over a long-term production is a difficult task, which is hardly achievable in construction sites. Therefore, the production variability should also be taken into consideration before loading the network of trade to full capacity and starting as many new constructions as possible, which is a common approach in the house building environment. Given the presence of variability, the number of unfinished jobs grows exponentially and the production system soon becomes unstable. Figure 7.7 shows how the size of the capacity buffer grows as a result of increasing the standard deviation of time between completions.

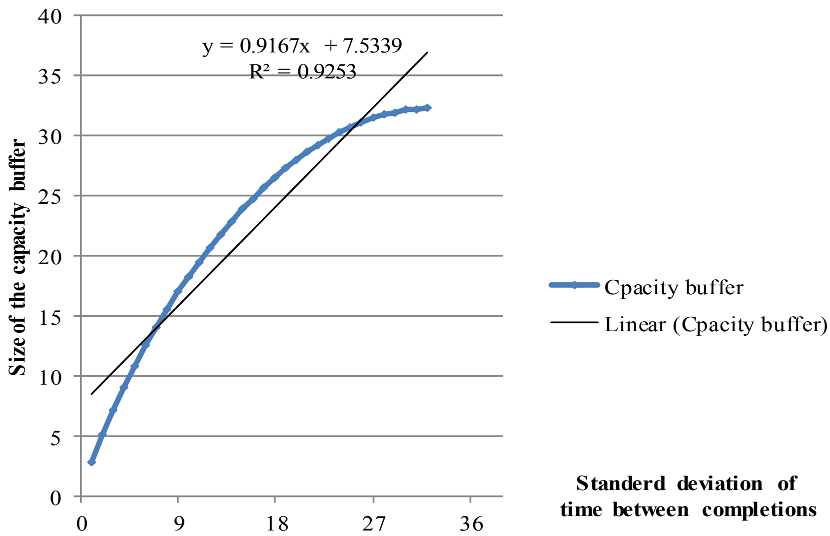


Figure 7.7. Impact of increasing production variability on size of the capacity buffer

The striking difference between Figures 7.6 and 7.7 highlights the high sensitivity of the capacity buffer size to the level of production variability. This is in line with the findings of González, Alarcón et al. (2009) and Rogalska and Hejducki (2007), indicating that focusing solely on capacity of the trade network can be misleading for builders and cause a lack of coordination between construction output and construction starts. In fact, without the aid of an optimal capacity buffer, target house completion (THC) and expected profit will decline over the long-term production. This is consistent with the results of running mathematical models in table 7.3 and validates them.

7.6. Chapter summary

Previous chapters of this thesis have documented the effectiveness of pull workflow in improving tangible performance measures in construction projects. Pull systems, however, do not consider due date integrity explicitly and an additional control measure in form of a capacity buffer is required (Yu 2011). Existing research in the construction literature in order to investigate effects of capacity buffers on production metrics and the optimal size for such a buffer is sparse.

To bridge this gap, this chapter tested a user-friendly framework for finding the optimal capacity buffer that maximises the workflow stability and minimises the probability of late completions. Towards this aim, production data of two volume house builders in Melbourne and Brisbane, Australia were collected and analysed. Having found the gross production capacity, using time series analysis, cost and capacity optimisations were conducted to find the optimal size of the capacity buffer. Following this, results of mathematical modelling were linked to a discrete-event simulation engine and different real-life production scenarios caused by varying stochastic variables of construction production were analysed.

The robustness of the framework in order to improve the workflow stability through establishing a capacity buffer was tested. Findings of this chapter show that an optimal-sized buffer can improve the ability of pull construction systems in maintaining a synchronised production in which output and demand are coordinated. These findings extend those of Nasir, Haas et al. (2012), Sacks and Barak (2008) and Ballard (2000), confirming the positive impact of reducing and buffering variability on improving the productivity in construction. In addition, the results show that setting the optimal capacity buffer requires making trade-offs between lost revenue opportunity caused by big buffers and late completion costs caused by small capacity buffers.

7.7. Chapter contributions and future research opportunity

The research conducted in this chapter contributes to the body of knowledge by developing a deeper understanding of the role of capacity buffers in improving workflow stability in the construction production. The proposed framework is intended to assist builders in finding the most cost-effective way to operate their network of trade contractors. Future work could also test its applicability in other construction settings rather than house building.

8. Chapter Eight – Maximising process flexibility in the FULFIL system of production control

8.1. Introduction

In chapter seven a tailored framework for buffering against variability in construction production was designed and tested. The framework enables production networks to find the optimal size for capacity buffers as oversized buffers are wasteful, hinder performance and impede workflow. Undersized buffers, on the other hand, increase the risk of late completions and a poor service level. Together with optimal-sized capacity buffers, a flexible workflow in the production network can improve performance substantially. Chapter eight focuses on the sixth research objective and investigates cross-training strategies for a flexible workforce in the FULFIL system. Although the analysis in this chapter focuses on offsite construction, findings have great potential to be used in both offsite and onsite construction.

Traditional approaches in construction project management assign each process to a trade contractor with an individual specialisation, and trades with the greatest work content (bottlenecks) have a significant influence on the progress rate of projects. An agile or flexible cross-trained workforce, however, is able to function dynamically in response to variability in product demand and labour resources. This chapter aims to compare and contrast cross-training strategies that would be applicable to the house building industry.

Construction sites are variable environments experiencing inclement weather conditions (Mills 2003, White 2004), quality problems resulting in rework (Palaneeswaran, Love et al. 2008, Arashpour, Wakefield et al. 2014), and shortage of specialised subcontractors (Landin 1995). The variability results in time and budget overruns, which are endemic problems in construction projects (Gibson Jr and Gebken Ii 2003). In order to reduce variability in onsite construction, prefabricated construction or offsite manufacture has received much attention in the industry (Courtney and Winch 2003, Larsson, Sundqvist et al. 2006, Pan, Gibb et al. 2008).

Prefabricated construction can improve performance measures because less time is spent on onsite operations and commissioning (Alvanchi, Azimi et al. 2011). It also improves quality through the trial and testing of products under factory conditions using consistent standards (Mwamila and Karumuna 1999). Furthermore, system performance in offsite construction is improved by lowering costs, and increasing added value and certainty, all of which facilitate more accurate measurement of productivity (Blismas, Wakefield et al. 2010). Finally, prefabricated construction can benefit logistics and site operations by reducing site disruptions, excessive subcontracting and spatial requirements (Warner, Schirmer et al. 2013).

Despite these benefits, prefabricated construction has been criticised as a replication of the traditional fragmented subcontracting approach in the construction industry. Offsite operations in a factory are undertaken by trades with individual specialisations that need substantial coordination to prevent work starvations in the production system (Blismas 2007). In other words, there is currently not much difference between onsite and offsite construction processes and initiatives used in other areas of manufacturing such as a flexible cross-trained workforce have not yet been implemented in the prefabricated construction sector (Arif, Bendi et al. 2012).

There is little research into optimal cross-training strategies in offsite construction and its benefits. In this chapter of the thesis, finding the optimal number of additional skills is formulated as a constrained optimisation problem. Then, different cross-training strategies and their effects on tangible performance measures are compared by means of simulation modelling. Production data from two prefabricated house factories in Melbourne and Brisbane, Australia were collected. In both cases, different components of a house such as roof trusses, frames, and wall panels are built in a production network. In the first step, tangible performance metrics are computed in the base case that is a production line with no flexibility (NF), entirely operated by individually specialised workers. Results of the base case are then compared to systems using five different cross-training strategies, Direct Capacity Balancing (DCB), Partial Skill Chaining (PSC), Closed Skill Chains (CSC), Hybrid Cross-Training (HCT), and Full Cross-Training (FCT).

The structure of this chapter of the thesis is as follows. First, the prefabricated house construction process and applicable cross-training strategies are described. Then, the optimal model for cross-training flexible workers is formulated as a constrained optimisation problem, leading to statement of the first proposition. Finally, data from two prefabricated house building factories are used to construct 1080 simulation experiments from which further propositions about optimal cross-training strategies are derived.

8.2. Background

In this section the typical process of building prefabricated houses is described. Next, different cross-training strategies to improve productivity in this sector are discussed.

Prefabricated house construction processes

Traditional ways of managing construction projects are inflexible and fragmented as each process is assigned to a trade contractor with an individual specialisation, and trades with the greatest work content have a significant influence on the progress rate of projects. In addition to improving this situation, prefabricated construction or offsite manufacturing can offer a great opportunity for alternative workforce training approaches in the industry. For example, in Australia, construction workforce undergoes long periods of apprenticeship in order to gain individual specialisations required for undertaking single construction processes. There are strong barriers of entry to other areas as it takes years to become fully licenced in a specialty. As a result, the construction industry is in continuous need of specialised trades who become scarce resources particularly during boom periods (Arashpour, Wakefield et al. 2013).

The house building sector can benefit greatly from offsite manufacturing. House building processes are very repetitive in nature and can be undertaken in the controlled environment of a factory instead of highly variable construction sites. Furthermore, offsite manufacturing of house components can offer mass customisation, modularisation and delayed product differentiation (Barlow, Childerhouse et al. 2003, Green and May 2003). Offsite production processes in the two case studies have been illustrated in the first Appendix of the thesis.

The delivery of construction projects is similar to processes in a typical assembly operation (Gibb and Isack 2003). In prefabricated house construction, different subcomponents such as wall frames, panels and roof trusses are made in a network of subassembly lines. The complete house package (final product) is made by merging subassembly lines. Figure 8.1 shows the processes in a prefabricated house factory where concrete panels and steel frames are the main subcomponents of a house.

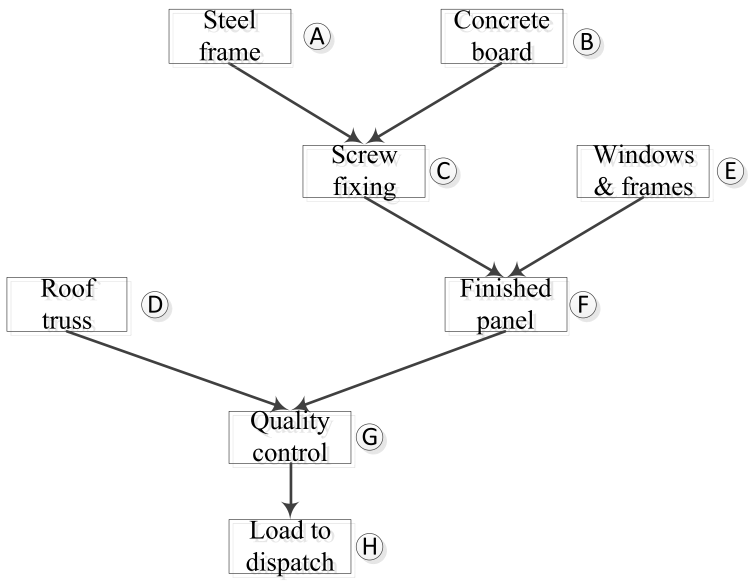


Figure 8.1. Prefabricated house construction network

The in-tree network in Figure 8.1 can be serialised using the technique used by Bartholdi III, Eisenstein et al. (2006), in which workstations are ordered based on continuity of workflow. That is, building a subcomponent of the house will progress as much as possible before making a new subcomponent. On this basis, it is preferable to undertake operations on the right branch of the Y-shaped line and finish building the panel before moving to the left branch to make the roof trusses. Figure 8.2 illustrates a serialised line for the building processes of a prefabricated house.

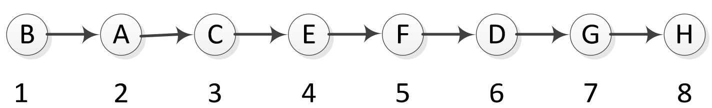


Figure 8.2. Serialised prefabricated house construction line

The fact that offsite construction operations are semi-automated and fairly simple makes cross-training approaches feasible. In onsite operations, cross-training is applicable on limited production zones, where there is similarity between processes. An agile or flexible cross-trained workforce is able to function dynamically in response to variability in product demand and labour resources.

8.3.Integrating construction processes

Process integration and cross-training can make production systems flexible. In such environments, workers are not restricted to performing a single task but are able to operate over a zone if partially cross-trained, or over the whole production line if fully cross-trained. Previous research has shown that cross-training enables production systems to share work dynamically and increase the production throughput rate (Lusby, Dohn et al. 2012, Azizi and Liang 2013, Hartenberger, Lorenz et al. 2013, Simmons 2013). It can also be motivating for workers as it reduces repetitive stress, fatigue and boredom (Burke, Curtois et al. 2010, Arashpour, Shabanikia et al. 2012). Workers can also enjoy more flexibility in taking leave as their task can be reallocated to other operators cross-trained to undertake the same task (Lind and Seigerroth 2003).

However, cross-training incurs cost. Full cross-training might be feasible in some industries such as apparel (Bartholdi III and Eisenstein 1996) but not in others such as car manufacturing or construction (Peters 2005, Layer, Karwowski et al. 2009, Moad 2009). In such environments, the best approach is to specify a throughput rate (TH) target and find the optimal cross-training strategy that enables the system to achieve that TH with minimal investment in additional skills (S^+). Cross-training strategies are briefly described in the following sections.

8.3.1. Direct Capacity Balancing (DCB)

The most intuitive strategy for cross-training is to compensate for work overload in bottleneck stations by borrowing the excess capacity of non-bottleneck operators (Lapierre and Ruiz 2004). In this setting, every worker is trained to cover processes in their primary station and a secondary station, which is always a bottleneck. Figure 8.3 shows that seven additional skills

(S^{+}) will be required in the previously illustrated production line when the fourth station has the greatest work content.

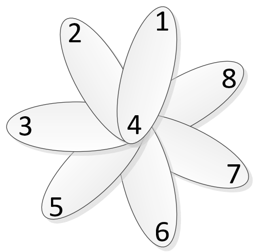


Figure 8.3. Direct capacity balancing: borrowing capacity from non-bottleneck operators

8.3.2. Partial Skill Chaining (PSC)

Workers can be cross-trained in order to operate in a limited zone of the production line. If there are overlapping work zones, workstations will be chained by means of flexible cross-trained workers (McDonald, Ellis et al. 2009, Gong, Wang et al. 2011, Andradõttir, Ayhan et al. 2013). This strategy helps to accelerate production processes in the bottleneck stations indirectly as not every worker is trained to cover bottlenecks. Figure 8.4 illustrates a production line where every worker is partially cross-trained to cover two consecutive stations, with the exception of the operator of station eight, which is the bottleneck in this case. As can be seen, S^{+} is equal to seven in this scenario.

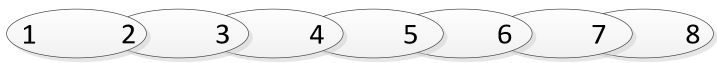


Figure 8.4. Partial skill chaining: bottleneck operator is not cross-trained

8.3.3. Closed Skill Chains (CSC)

In this approach every worker is cross-trained, even bottleneck trades. CSC can prevent occasional work starvations of bottleneck operators and improve production performance (Hopp and Van Oyen 2004). This is applicable in production cells or U-shaped lines where workers do not have to spend unproductive time in order to walk between stations (Lim and Wu 2013).

Figure 8.5 shows a construction production network with a closed skill chain. Eight additional skills (S^{+}) are required in this setting.

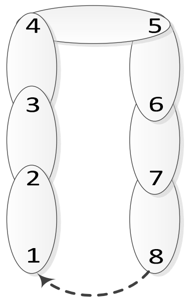


Figure 8.5. Closed skill chain in a U-shaped production cell

8.3.4. Hybrid Cross-training (HCT)

Skill chaining (SC) has the potential to buffer the variability in production systems. Within the construction context, however, processing times are often highly imbalanced (Skitmore and Cattell 2013). In cases where both imbalance and variability is significant, SC can be implemented together with direct capacity balancing (DCB) to create an optimal cross-training strategy (Hopp, Iravani et al. 2005, Hopp, Iravani et al. 2009). That is, flexible workers are capable of covering a zone in the production line as well as bottleneck stations. Figure 8.6 illustrates the hybrid cross-training strategy in the offsite construction network where S^{+} is equal to 15. Results of simulation experiments in the next section will show that the hybrid strategy can result in throughput rates that are almost equal to full cross-training (FCT), which needs 56 additional skills in the production network illustrated in Figure 8.1.

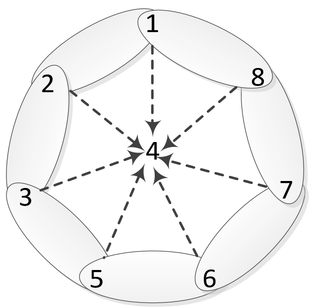


Figure 8.6. Hybrid cross-training in a production cell

8.4. Variability buffering

Some operations in prefabricated house construction are longer than others, causing the production line to become imbalanced. Different production rates mean that workstations and their relative resources are either over utilised (bottlenecks) or underutilised (non-bottlenecks). There are different approaches to buffer the variability in process times and prevent delays. Work-in-process (WIP) buffers can be used in order to increase the utilisation of resources and avoid work starvations (González, Alarcón et al. 2011) but oversized buffers are wasteful, hindering performance and impeding the workflow (Horman and Thomas 2005). Another approach to balance production, which is the focus of this chapter, is to integrate work processes and use a flexible cross-trained workforce, in which capacity is borrowed from underutilised trades to help over utilised trades.

8.5. Optimal process integration strategy in production lines with an output rate target

Since every worker has a unique productivity level, individual performance can be benchmarked against the exemplar performance of a standard worker (Shao, Yin et al. 2013). In measuring Performance ability ratio (PAR), different factors such as work velocity and work quality are taken into consideration, as productivity is not all about speed of producing an output (Leaman and Bordass 1999, Crawford and Vogl 2006, Koskela and Ballard 2006). For every worker PAR_w can be defined as,

$$PAR_w = \frac{P^o}{P^s} \tag{8.1}$$

In equation (8.1), P^o is the productivity measure of an observed worker and P^s is the standard (estimated) productivity. On this basis, PAR for a standard worker, with a reasonable work velocity and quality, is equal to one. For a very productive worker, PAR will be greater than one and for a less productive workforce, it will be close to zero.

For a standard worker, the mean processing time at station K is denoted by T_k. So for worker W, the mean processing time at station K is ${T_k}/{PAR_w}$. The estimated line throughput ($\widehat{TH}$) that can be achieved by full cross-training is computed using a similar equation to that proposed by Hopp and Spearman (2008),

$$\widehat{TH} = \frac{\sum_1^k PAR_w}{\sum_1^k T_k} \qquad (8.2)$$

Since the learning of additional skills by flexible workers to cover other stations in addition to their primary tasks incurs cost, it is not always feasible to fully cross-train the workforce. In this chapter, an optimal level of cross-training is sought that leads the system to achieving $\widehat{TH}$. Some researchers have solved this as a constrained optimisation problem to find the minimal number of additional skills necessary in serial production lines (Agnihothri, Mishra et al. 2003, Hopp, Tekin et al. 2004, Bartholdi III, Eisenstein et al. 2006, Campbell 2011). The objective in this chapter is to minimise the number of additional skills while achieving a specified throughput target ($\widehat{TH}$). Consider that the prefabricated house production line has K workstations, each attended by one specialised worker. To achieve the throughput rate of $\widehat{TH}$, every station requires enough capacity to process jobs at a balanced rate. Since workers have different performance ability ratios, there is a level of capacity imbalance (LCI) for worker W that covers station K. Level of capacity imbalance can be computed using equation (8.3),

$$LCI = \left| PAR_w \left(\frac{\widehat{TH} \times T_k}{PAR_w} - 1 \right) \right| = \left| \widehat{TH} \times T_k - PAR_w \right| \qquad (8.3)$$

For example, consider that the specified throughput target of the line is one completed house every seven time units. If the required processing time in station K is eight time units and worker W has a standard processing rate with performance ability ratio of $PAR = 1$, then $\widehat{TH} \times T_k - PAR_w$ will have a positive value. This indicates that station K has a capacity deficiency (D_k) and needs to borrow additional capacity from other underutilised workers. In this case, one or more workers have to learn one additional skill in order to cover station K. Under the same setting but when the processing time of station K is reduced to six time units, $\widehat{TH} \times T_k - PAR_w$ will be negative, indicating that worker W has excess capacity (E_w). Provided that worker W has been cross-trained, excess capacity can be used to help bottleneck stations.

Consider a line with K stations, which B of them have longer than average processing times (bottlenecks). The number of man-hours that cross-trained worker W with extra capacity allocated to station K with capacity deficiency is x_{wk}. Figure 8.7 illustrates the allocation of the workers' excess capacity to bottleneck stations.

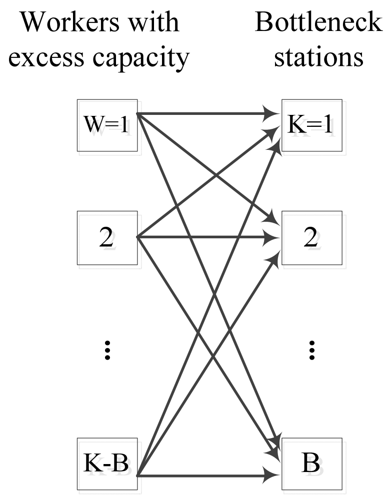


Figure 8.7. Skill sharing in a production network with K stations

The objective is to minimise the amount of cross-training or in other words the number of additional skills (S^{+}),

$$Min\ S^{+} = \sum_{w=1}^{K-B} \sum_{k=1}^{B} x_{wk} \tag{8.4a}$$

The first constraint limits the number of man-hours that workers can attend secondary (bottleneck) stations to the available excess capacity,

$$\sum_{k=1}^{B} x_{wk} \leq E_w \tag{8.4b}$$

Another constraint results because the number of allocated man-hours from underutilised workers to bottlenecks is always less than the capacity deficiency,

$$\sum_{W=1}^{K-B} x_{wk} \leq D_k \tag{8.4c}$$

Finally, the last constraint enforces a balanced line. That is, sum of workers' excess capacities is equal to the sum of bottleneck capacity deficiencies,

$$\sum_{W=1}^{k-B} E_w = \sum_{k=1}^{B} D_k \tag{8.4d}$$

Expressions (8.4a) to (8.4d) formulate the cross-training problem as a transportation problem. Accordingly, the first proposition in this chapter is advanced as:

Proposition 1 Finding the optimal number of additional skills in an offsite construction environment with flexible cross-trained workers can be formulated as a transportation problem with fixed edge costs.

In order to measure impacts of process integration on tangible performance measures, average utilisation levels for labour resources in the base case (NF) and five proposed cross-training strategies are plotted in Figure 8.8. The strategies under investigation are: direct capacity balancing (DCB), partial skill chaining (PSC), closed skill chains (CSC), hybrid cross-training (HCT), and full cross-training (FCT).

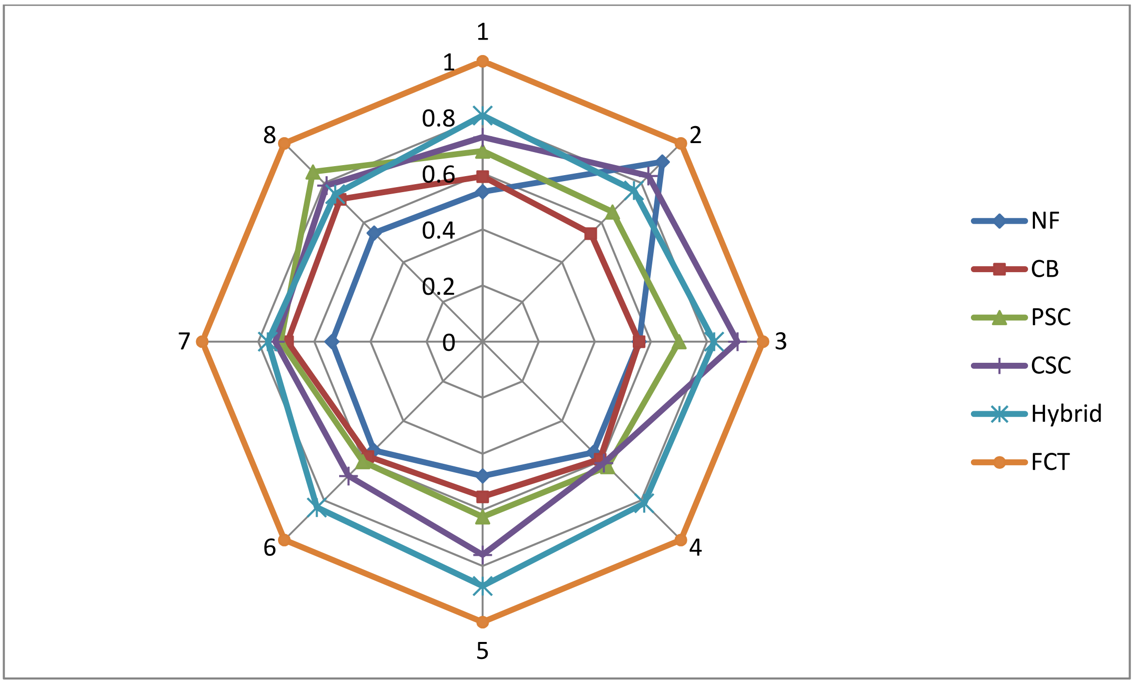


Figure 8.8. Labour resource utilisations in different process integration strategies

As can be seen in Figure 8.8, when there is no process integration and the system is not flexible (NF), resource utilisation levels are very imbalanced. Implementation of more comprehensive cross-training strategies results in higher levels of resource utilisation and consequently reduces the completion times. In order to further investigate the benefits of cross-training strategies, their impact on completion times was plotted in Figure 8.9 and results of the simulation study for different cross-training strategies (DCB, PCT and HCT) were superimposed on the base case (NF).

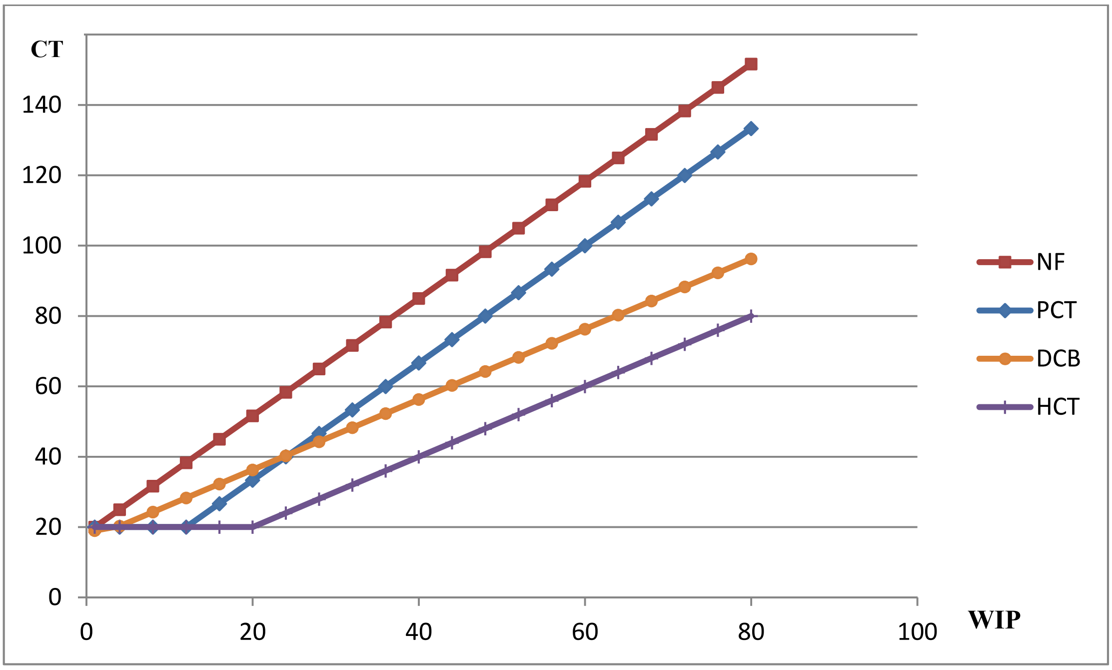


Figure 8.9. Cycle time versus Work-in-process in different cross-training scenarios

As expected, investment in a larger number of additional skills (S^{+}) and adopting the hybrid cross-training strategy results in shorter house completion times. Surprisingly, direct capacity balancing (DCB) outperforms partial cross-training (PCT) by resulting in shorter house completion times. It is worth mentioning that this only happens when the work-in-process level is more than 24 jobs. That is, flooding the production network with WIP has the same variability buffering effects as skill chaining strategies but excessive WIP hinders performance and impedes the workflow.

In prefabricated construction, swift delivery of the final product is the major concern of both house builders and buyers. As can be seen in Figure 8.9, successive upgrades from a system with specialised workers to a flexible system with cross-trained workers reduce cycle times significantly and create competitive advantage for offsite house manufacturers. This saving in time is also achievable in onsite construction production, in which integrating processes by cross-training is possible over limited production zones where processes are more similar.

In order to compare performances of different cross-training strategies in a moderately sized production network, in a similar approach to Hopp, Tekin et al. (2004), simulation was used in the next part of this research.

8.6. Performance of process integration strategies

In this section, performance of different cross-training strategies is compared in a moderately sized prefabricated house production network (see Figure 8.1). The base case is a line with no flexibility (NF) where all workers are specialists. Five cross-training strategies under investigation are: direct capacity balancing (DCB), partial skill chaining (PSC), closed skill chains (CSC), hybrid cross-training (HCT), and full cross-training (FCT).

Method of investigation

In order to compare the performance of different cross-training strategies, discrete event simulation (DES) was used. DES is the most frequently used technique in classical operational research studies across a range of industries (Hollocks 2006, Feng and Fan 2013). Simulation models are powerful tools to assist managerial decision-making (Olson, Shipley et al. 2006) and when constructed precisely can yield valid results (Reis Dos Santos and Reis Dos Santos 2011). Prefabricated house construction processes were simulated using a computer program written in SIMAN. Care was taken to build precise models that reflect the reality in the production environment. Figure 8.10 shows a snapshot of the SIMAN coding window for this purpose.

```
DSTATS:         Total WIP,Total WIP Value,,DATABASE(,"Variable","User Specified","Total
WIP");

OUTPUTS:        Stack into Loading Racks.NumberOut,,Stack into Loading Racks Number
Out,DATABASE(,"Number Out","Process",
                "Stack into Loading Racks"):
                Concrete board.NumberOut,,Concrete board Number Out,DATABASE(,"Number
Out","Process","Concrete board"):
                Door Win. Aluminium Frame.VATime,,Door Win. Aluminium Frame Accum VA
Time,DATABASE(,"Accum VA Time","Process",
                "Door Win. Aluminium Frame"):
                Panel Finishing.NumberOut,,Panel Finishing Number Out,DATABASE(,"Number
Out","Process","Panel Finishing"):
                Concrete board.WaitTime,,Concrete board Accum Wait Time,DATABASE(,"Accum
Wait Time","Process","Concrete board"):
                Panel Screw Fixing.NumberIn,,Panel Screw Fixing Number In,DATABASE(,"Number
In","Process","Panel Screw Fixing"):
                Door Win. Aluminium Frame.NumberIn,,Door Win. Aluminium Frame Number
In,DATABASE(,"Number In","Process",
                "Door Win. Aluminium Frame"):
                Quality inspection of Building Components.VATime,,Quality inspection of
Building Components Accum VA Time,DATABASE(,
                "Accum VA Time","Process","Quality inspection of Building Components"):
                Roof Truss Steel Frame.VATime,,Roof Truss Steel Frame Accum VA
Time,DATABASE(,"Accum VA Time","Process",
                "Roof Truss Steel Frame"):
                Steel Frame.NumberIn,,Steel Frame Number In,DATABASE(,"Number
In","Process","Steel Frame"):
                Panel Screw Fixing.WaitTime,,Panel Screw Fixing Accum Wait
Time,DATABASE(,"Accum Wait Time","Process",
                "Panel Screw Fixing"):
                Quality inspection of Building Components.NumberOut,,Quality inspection of
Building Components Number Out,DATABASE(,
                "Number Out","Process","Quality inspection of Building Components"):
                Roof Truss Steel Frame.NumberOut,,Roof Truss Steel Frame Number
Out,DATABASE(,"Number Out","Process",
                "Roof Truss Steel Frame"):
                Steel Frame.WaitTime,,Steel Frame Accum Wait Time,DATABASE(,"Accum Wait
Time","Process","Steel Frame"):
                Door Win. Aluminium Frame.WaitTime,,Door Win. Aluminium Frame Accum Wait
Components Number In,DATABASE(,
                "Number In","Process","Quality inspection of Building Components"):
                Steel Frame.NumberOut,,Steel Frame Number Out,DATABASE(,"Number
Out","Process","Steel Frame"):
                Roof Truss Steel Frame.WaitTime,,Roof Truss Steel Frame Accum Wait
Time,DATABASE(,"Accum Wait Time","Process",
                "Roof Truss Steel Frame"):
                Panel Screw Fixing.VATime,,Panel Screw Fixing Accum VA Time,DATABASE(,"Accum
VA Time","Process",
                "Panel Screw Fixing"):
                Quality inspection of Building Components.WaitTime,,Quality inspection of
Building Components Accum Wait Time,
                DATABASE(,"Accum Wait Time","Process","Quality inspection of Building
Components"):
                Concrete board.VATime,,Concrete board Accum VA Time,DATABASE(,"Accum VA
Time","Process","Concrete
REPLICATE,      100,,,Yes,Yes,DaysToBaseTime(79),TNOW >= 365,,8,Days,No,No,,,Yes,No;
SETS:           Set 1,Concrete Board Worker,Loading worker,Quality Worker,Roof Truss
Worker,Panel Finishing Worker,
                Aluminium Frame Worker,Screw fixing Worker,Steel Frame worker:
                Set 2,Steel Frame worker,Concrete Board Worker:
                Set 3,Screw fixing Worker,Steel Frame worker:
                Set 4,Aluminium Frame Worker,Screw fixing Worker:
                Set 5,Panel Finishing Worker,Aluminium Frame Worker:
                Set 6,Roof Truss Worker,Panel Finishing Worker:
                Set 7,Quality Worker,Roof Truss Worker:
                Set 8,Loading worker,Quality Worker;
```

Figure 8.10. SIMAN code defining the cross-training strategy in simulation experiments

A total of 1080 simulation experiments were designed, each simulated for 365 working days with a warm up period of 79 days. One hundred replications of each experiment resulted in desired confidence level of 99% with all standard errors within 0.2%.

In order to impose different levels of capacity imbalance, different system designs with 1, 2 and 4 bottleneck stations were investigated. In each design, the bottleneck processing times were set to be 25%, 50%, 75% and 100% greater than non-bottlenecks. The coefficient of variability (CV) was set to 0.2, 1 and 3 to represent low, significant and high variability in processing times and availability of labour resources.

Six approaches towards cross-training were compared: NF, DCB, PSC, CSC, HCT, and FCT. Work-in-process (WIP) inventories were set to 8, 16, 24, 40 and 80 jobs. Overall, 1080 experiments were constructed using different combinations of three bottleneck designs, four levels of capacity imbalance, three CV values, six cross-training strategies, and five WIP levels.

While the method of investigation is similar to Hopp, Tekin et al. (2004), their study compared different cross-training strategies in serial production lines. However, this chapter investigates benefits of different cross-training strategies in an in-tree assembly network of prefabricated house production. The biggest challenge was to introduce different cross-training strategies to the production system. A special-purpose simulation code was written in SIMAN in order to create diverse skill sets used in the experiments.

8.7. Verifying and validating the simulation model

The process of verification ensures that the behaviour of the model is consistent with the way it intends to behave and in accordance with modelling assumptions (Liu 2010). In other words, verification means building a simulation model right. To this end, the model was double checked to find possible errors in data entry and unit consistency. Counter constructs were used in order to collect statistics on inputs to the model. Then input was checked to be equal to the sum of the work-in-process inventory and the output of the model. Long periods of simulation runs proved that there are no deadlocks in the model architecture. Operation animations and a slow model run ensured that the entities were routed into intended subassembly lines and the model behaved logically. Upon the completion of these steps, computer implementation of the model was reasonably considered to be error free (debugged) and verified.

The process of validation ensures that the model behaves the same as the real-world system (Fellows and Liu 2008). In other words, validation means building a correct simulation model. To this end, case study participants were briefed about the assumptions and methodology used to develop the model and the way historical data were treated to determine probability distributions. Agreement of participants upon all modelling assumptions resulted in development of models with high face validity. Furthermore, the current production processes of the two systems were modelled and run 100 times. Throughput rates and cycle times were checked against the data collected from March to November 2013. The simulation results and real-world production data were almost identical, with errors within the range of 0.2%. Table 8.1 shows the comparison between observed completion times and the results of simulation.

Table 8.1. Comparison of actual completion times with simulation results

Month	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.
CT (collected data)	0.700	0.735	0.809	0.801	0.754	0.718	0.697	0.699	0.701
CT (simulation)	0.701	0.735	0.807	0.802	0.754	0.719	0.695	0.699	0.699
Error %	0.0014	0.0000	0.0020	0.0012	0.0000	0.0013	0.0020	0.0000	0.0020

In the next step, well-founded models such as Little's law (Little 1961) were used to compute the production parameters, which were found to be consistent with those of the simulation model. Finally a sensitivity analysis on results, which was conducted by slight manipulation of the model input variables found no extreme variations in results. With the completion of these steps, the model was considered validated and reasonably robust.

8.8. Results and analysis of the simulation study

Data from two prefabricated house production systems in Melbourne and Brisbane were fed to the simulation models. Tangible system performance metrics for different cross-training scenarios were measured such as throughput rate (TH), cycle time (CT), average labour resource utilisation level (U), number of house completion, and percentage of improvement in TH comparing with the nonflexible base case. Results for a randomly selected line with $CV = 1$, capacity imbalance of 25% and $WIP = 16$ are presented in Table 8.2.

Table 8.2. Effect of different cross-training strategies on tangible performance measures

Cross-training	S^{+}	*TH*	*CT*	*U*	House completions	Improvement in TH than NF
NF	0	0.580	27.6	0.79	166	0
DCB	7	0.636	25.2	0.86	182	9%
PSC	7	0.675	23.7	0.92	193	16%
CSC	8	0.710	22.5	0.98	205	22%
HCT	15	0.710	22.5	0.98	205	22%
FCT	56	0.727	22.0	1.00	208	25%

As can be seen in table 8.2, when workers are not flexible and they are specialised to cover single work stations, there are 166 house completions. Throughput rate (TH) significantly increases by 9% when workers are trained to cover a bottleneck station in addition to their primary work station (direct capacity balancing). This result is consistent with previous studies (Sennott, Van Oyen et al. 2006, Arashpour, Wakefield et al. 2013), confirming that investment in training a flexible workforce will be offset by the increase in production output rates.

Another significant result is derived from comparison of partial skill chaining (PSC) and direct capacity balancing (DCB). A further improvement of 7% in TH was observed by switching from DCB to PSC and training workers to cover an adjacent work station in order to create skill chains. It is worth mentioning that no additional investment in training programs is required as the number of additional skills is equal to seven in both scenarios. Our findings for in-tree assembly networks are in line with those of Hopp, Tekin et al. (2004) for serial production lines. The second proposition of this chapter is derived from this result:

Proposition 2 In offsite construction networks with variable processing times and low levels of work-in-process (lean production), it is optimal to cross-train workers in an indirect path to the bottlenecks (PSC) than directly train them to cover the bottlenecks (DCB).

Table 8.2 also shows that adding only one more additional skill ($S^+ = 8$) upgrades the cross-training strategy to a closed skill chain (CSC) and throughput rate grows by 6% more than PSC. In fact, the small investment in training the bottleneck operator to cover the adjacent non-bottleneck station results in a substantial improvement in the system performance. Understandably, production systems such as those in Figure 8.5 and Figure 8.6 have ideal layouts for implementing CSC as workers do not have to spend a long period of unproductive time walking between stations. This leads us to the development of the next proposition of this chapter:

Proposition 3 Completing the skill chain by training the bottleneck operators to cover an adjacent work station is the optimal cross-training strategy to achieve a target throughput in offsite construction networks with significant variability and low levels of work-in-process.

Trade-offs should be made in the selection of process integration strategies in production environments. For example, using hybrid cross-training with 15 or full cross-training with 56 additional skills would not be justifiable, considering the small increases in the throughput rate. This confirms that using comprehensive training programs such as HCT and FCT are only feasible in presence of both high capacity imbalance and variability.

It is the capacity balancing and variability buffering capabilities of cross-training strategies that prevent flexible workers from work starvations in the production network, resulting in high levels of resource utilisation. Table 8.3 shows average utilisation levels for labour resources in the base case (NF) and five investigated cross-training scenarios.

Table 8.3. Labour resource utilisation levels in different cross-training scenarios

Labour resource	NF	DCB	PSC	CSC	HCT	FCT
Concrete board	1.0000	0.6032	0.7390	1.0000	0.9339	1.0000
Steel frame	0.7907	0.9460	1.0000	0.9877	0.9857	1.0000
Panel screw fixing	0.7572	0.9017	0.9945	0.9757	0.9931	1.0000
Windows and frames	0.7509	0.8782	0.9735	0.9459	0.9968	1.0000
Panel finishing	0.7651	0.8930	0.9604	0.9449	0.9938	1.0000
Roof truss	0.7531	0.8871	0.8977	0.9658	0.9919	1.0000
Quality control	0.7736	0.8838	0.9604	0.9877	0.9856	1.0000
Load to dispatch	0.7123	0.9028	0.8512	0.9951	0.9398	1.0000

When trades are individually specialised and production is not flexible (NF), concrete board workers are fully utilised (bottleneck). Adopting the strategy of direct capacity balancing (DCB) seems to be excessive as it makes the concrete board worker the least utilised labour resource. In partial skill chaining (PSC), however, the situation in DCB is improved but the adjacent labour resource to the bottleneck (steel frame worker) becomes the highest utilised resource as the task is only covered by a single resource.

A closed skill chain strategy behaves more optimally than DCB and PSC. Under this strategy, the highest utilisation level still belongs to the labour resource with the greatest work content (concrete board) and other resources are utilised almost fully, representing a balanced and efficient production network. It is worth mentioning that adopting cross-training strategies enables the offsite construction system to maintain low levels of work-in-process (WIP). Excessive WIP inventory is an expensive and wasteful means of buffering against the variability, which hinders performance and impedes the workflow. In this chapter the value of cross-training strategies was not biased by flooding the production network with WIP.

8.9. Value of hybrid cross-training in offsite construction

The capacity balancing potential of DCB and variability buffering capability of PSC were observed in previous sections. However, in highly variable and imbalanced production networks, the individual use of these strategies will not be enough. Based on results from the simulation study, a hybrid cross-training strategy can substantially improve tangible performance measures. Results for a line with $CV = 3$, capacity imbalance of 75% and $WIP = 8$ are presented in Table 8.4.

Table 8.4. Effect of different cross-training strategies on tangible performance measures

Cross-training	S^{+}	TH	CT	U	House completions	Improvement in TH than NF
NF	0	0.154	52	0.58	44	0
DCB	7	0.157	51	0.60	45	2%
PSC	7	0.185	43	0.68	53	20%
CSC	8	0.200	40	0.75	57	29%
HCT	15	0.220	36	0.80	63	43%
FCT	56	0.273	29	1.00	78	77%

As can be seen in table 8.4, upgrading the cross-training strategy to HCT increases the throughput rate by 43% comparing to the base case. In fact, a hybrid use of cross-training strategies can simultaneously solve two common problems of high capacity imbalance and variability in offsite construction. Since the number of additional skills in the production network is only 15, investments are likely to be offset by the growth in throughput rate. This result in assembly networks are consistent with findings of Hopp, Tekin et al. (2004) for serial production lines and leads to the fourth proposition of this chapter:

Proposition 4 In the presence of high capacity imbalance and variability in offsite construction networks, using a hybrid strategy (direct capacity balancing + skill chaining) is the optimal cross-training approach in order to yield a specified throughput target.

It is worth mentioning that improvements made by using the propositions in this chapter are also achievable in onsite construction production, in which integrating processes by cross-training is possible over limited production zones where processes are more similar in nature.

8.10. Chapter summary

Despite previous research that shows the advantages of offsite construction (Blismas, Pasquire et al. 2006, Pan, Gibb et al. 2012), few studies tested the applicability of process integration strategies in this production environment in order to increase flexibility in the workflow. To bridge this gap, this chapter compares the performance of different cross-training strategies in construction production using data collected from two offsite construction facilities in Melbourne and Brisbane, Australia.

Findings in this chapter show that when capacity imbalance is the only issue in the system, it can be addressed by borrowing capacity from underutilised trades (non-bottleneck processes) and helping over-utilised trades (bottleneck processes). On the other hand, when processing times are variable, indirect skill chaining is the optimal policy. That is, stations are covered by more than one trade and capacity is shifted in an indirect path to the bottlenecks. Finally, when both capacity imbalance and variability are significant, the hybrid use of both solutions can best boost production performance. Findings in chapter eight extend those of Hopp, Tekin et al. (2004) who focused on serial production lines. This investigation therefore indicates that process integration can be employed as an effective strategy in order to improve flexibility in the workflow.

8.11. Chapter contributions and future research opportunity

This chapter contributes to the body of knowledge by expanding the insight into benefits of different process integration strategies in offsite construction networks. Furthermore, practitioners in the construction industry can use the propositions to make optimal decisions regarding the investment in cross-training.

A number of extensions to the present work are recommended. The applicability of cross-training a flexible workforce in other construction environments rather than house building could be investigated. Furthermore, fundamental human behaviour issues such as motivation, learning curve and communication significantly affect the success of any cross-training program, and require further research in a construction context. Finally, operational-level models could be used to investigate the implementation of process integration architectures and their effect on work-sharing in production networks.

9. Chapter Nine – Minimising interruptions caused by quality problems in the FULFIL system of production control

9.1. Introduction

In chapter eight the possibilities for maximising workflow stability were investigated. It was found that construction production can be balanced by using cross-training strategies. In choosing the optimal strategy, trade-offs should be made based on the level of imbalance and variability in processing times, and the required investment in cross-training. A flexible workflow can reduce the number of uncompleted jobs and congestion in the production network and reduce the likelihood of having quality problems and rework. Chapter nine focuses on the seventh research objective and intends to minimise the interruptions caused by rework.

Operational performance in residential construction production systems is assessed based on measures such as average house completion time, number of houses under construction, lead time and customer service. These systems, however, are prone to non-uniformity and interruptions caused by a wide range of variables such as inclement weather conditions, accidents at worksites, fluctuations in demand, and rework. The availability and capacity of resources therefore are not the sole measures for evaluating construction production systems capacity, especially when rework is involved. The aim of this chapter is to investigate the effects of rework interval and duration on tangible performance measures. Furthermore, different call-back timeframes for rework and their impact on house completion time are modelled and analysed.

In construction production, rework can interrupt workflow in different ways. Faults in the work of trade contractors are inspected internally by the builder's supervisors or externally by building surveyors or another third party. The responsible trade contractor is then called back to rectify the fault. In an ideal situation rework is executed between other construction processes (Arashpour, Shabanikia et al. 2012). However, it often becomes priority work that should be undertaken immediately (Sawhney, Walsh et al. 2009). Furthermore, length and frequency of rework can affect production performance significantly. Modelling the detailed process of rework in construction, which is analogous to "re-entrant flow" in production systems, has been regarded as difficult in the literature and requiring more research and investigation (Damrianant and Wakefield 2000, Brodetskaia, Sacks et al. 2013).

To bridge this gap, this chapter uses an innovative approach tailored to the construction context, in order to model and analyse interruptions of different kinds. Twelve experiments have been designed by varying: (1) the length of interruptions caused by rework; (2) frequency of rework; (3) the timeframe of call-backs for rework. Both analytical and simulation modellings have been used to robustly compare and contrast performance measures in presence of these variables.

9.2. Background: Causes of construction rework

In this section, previous works that have focused on causes of construction rework are reviewed.

There are many discussions around rework in the construction literature. Contributors to rework can be classified into some main categories: construction planning and scheduling, engineering and reviews, human resource capability, material and equipment supply, and leadership and communication (Fayek, Dissanayake et al. 2004). Under such classification, root causes of construction field rework involve but are not limited to: constructability problems (Feng 2009), unrealistic schedules (Love, Edwards et al. 2010), changes in project scope (Tuholski 2008), poor document control (Love, Edwards et al. 2009), unclear instruction to workers (Thompson and Perry 1992), insufficient skill levels (Mubarak 2010), lack of safety (Del la Garza, Hancher et al. 2000, Rajendran, Gambatese et al. 2009), ineffective project management team (Love, Holt et al. 2002, Choi, Kwak et al. 2011), untimely supply of materials (O'Brien, Wang et al. 2006, Hwang, Park et al. 2012), and non-compliance with specifications (Sawhney, Bashford et al. 2005).

Concurrency in the project execution is another contributor to rework. As short time-to-market is becoming more important in today's construction industry, processes are started before their predecessors are completely finished. Although the so called management strategy of fast tracking can help meeting the scheduled due dates and therefore greater market share, it can add hidden costs such as rework costs to projects (Salazar-Kish 2001, Touran 2010). Project management tools such as Critical Path Method (CPM) do not capture these and decisions on rework are made based on managers' judgment. Therefore finding new approaches to model rework and quantitatively measuring its effect on production parameters are of the great importance. Discrete event simulation (DES) is a useful tool to research construction processes and rework (Martinez 2010).

Another stream of research adopted mathematical and graphical modelling tools such as Petri Nets (PNs) in order to enhance modelling of construction processes. Petri Nets methodology

(Petri 1966) facilitates a realistic modelling of delays in the process of construction. For example, Wakefield and Sears (1997) and Sawhney, Abudayyeh et al. (1999) used Petri Nets for simulation and modelling of construction systems. However, only a few studies have investigated the interferences in construction processes using mathematical modelling. Damrianant and Wakefield (2000) and Lu and Ni (2008) used time and colour Petri nets to model interruptions in discrete-event systems. In the limited available studies, over-simplistic assumptions such as deterministic process times and interruption durations have made the models too distant from the reality of construction sites.

Modelling interruptions between and during processes has been regarded as difficult in the literature, requiring more research and investigation (Damrianant and Wakefield 2000, Boukamp and Akinci 2007). The present chapter aims to bridge this gap and minimise impacts of quality related delays on construction production.

9.3. Modelling of construction production processes

Construction processes are usually modelled in an interdependent network of predecessors and successors. For example, in the common scenario in Australia, volume house builders subcontract up to 100 processes to about 50 specialized trade contractors (Dalton, Hurley et al. 2013). The common production strategy is make-to-order and there is usually no building on speculation. Builders' superintendents or construction supervisors are responsible for managing movement of work (handoffs) among trade contractors. Upon completion of a process, trade contractors release their resources and engage them again in the next job. There are two main requirements for starting a process at its scheduled time: timely completion of preceding processes, and delivering high quality work without need to call-back for rework. As an example, roofing contractor is dependent on the timely and quality work of framing trade contractor as their predecessor and a call-back is required upon existence of faults in roof trusses.

Construction processes are resource constrained and can only be executed when required resources such as labour, material and information are available. As an example, the process of concreting the foundation slab as part of the production house building network is illustrated in Figure 9.1.

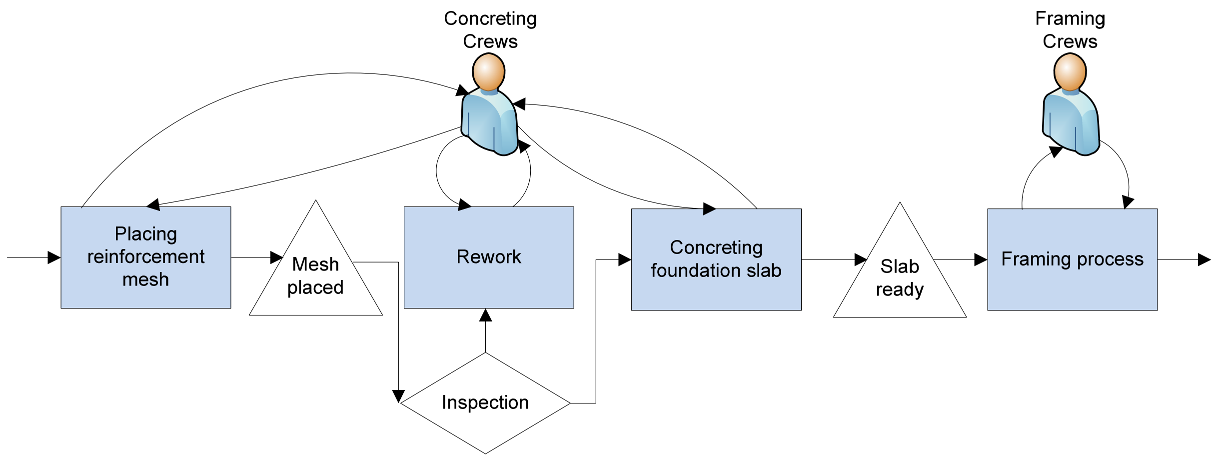


Figure 9.1. Process of concreting foundation slab as a part of production house building

The complete model of production house building including 50 trade contractors that are responsible for about 100 processes was developed using the same method as Yu (2011). The focus of the model, which is illustrated in a subsequent section on the chapter, is on workflow between resources.

9.4. Modelling of interruptions caused by rework

In practice frequency and duration of rework can affect completion times among other production parameters (Sawhney, Walsh et al. 2009). Furthermore, the timeframe in which rework call-backs occur changes the interruption length and effect. Three possible timeframes for call-backs (rework orders) are discussed in the following sections:

9.4.1. On time call-backs for rework before releasing resources

The rework is usually ordered when a given construction process has been completed. In Australia, building surveyors carry out four external inspections on major building stages – foundation, framing, lock-up/waterproofing, and pre-occupancy. In addition, within-organization inspections are conducted by builders to identify any fault. In the event of a fault, responsible trade contractor is called back to rectify it. After the necessary rework has been done, the following trade contractor can then initiate their process. Figure 9.2 presents the timescale for foundation rework before the resources have been released.

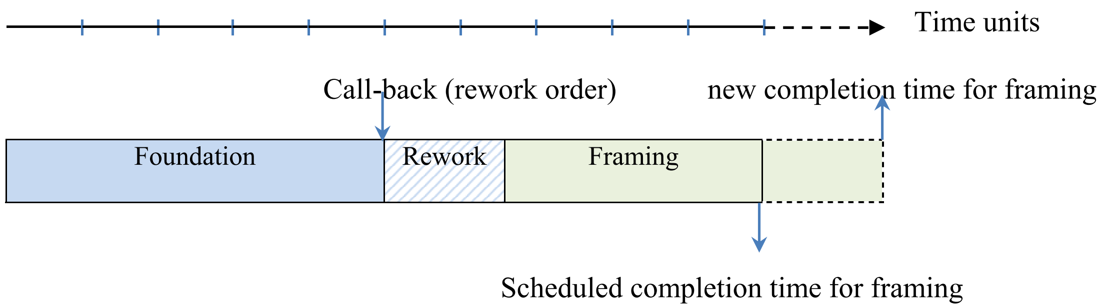


Figure 9.2. Timescale for call-back and rework before releasing resources

Understandably a later completion time is expected as the rework duration pushes back the scheduled completion of process.

9.4.2. Late call-backs for rework after releasing resources

Faults are sometimes discovered after initiation of the construction processes that follow. In such a situation, call-backs for rework are made after the responsible trade contractor has left the site and resources have been released. In this case, rework becomes priority work for the responsible trade contractor (Sawhney, Walsh et al. 2009). This is unique to construction industry – in manufacturing for example, rework is commonly regarded as a non-preemptive failure, which can be performed between processes (Hopp, Iravani et al. 2011). Figure 9.3 illustrates the timescale for foundation rework after foundation trade has left the worksite.

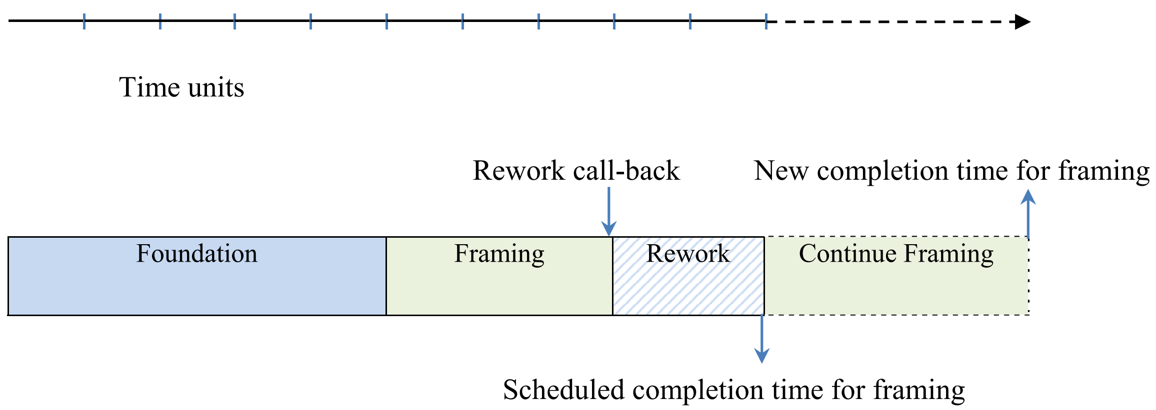


Figure 9.3. Timescale for call-back and rework after releasing resources

In Figure 9.3, the late call-back for rework causes the framing process to be broken into separate parts and therefore has the potential to create long delays. Sometimes framing crew are available when called back after completion of the foundation rework. In most cases, however, trade contractors are not dedicated to a single project, and will leave to do another job while their processes are interrupted and may be unavailable to continue work until the other job is completed. This further lengthens delays.

9.4.3. Early call-backs for rework prior to process completion- collaborated hand-offs

Effective supervision and coordination of construction can result in call-backs for rework being made during the execution of a given process. In this way, the responsible trade contractor for the rework is able to use already engaged resources to rectify the fault. Upon the availability of sufficient resources, the trade contractor may be able to complete rework using some of the crew while others move to the next job. This is only possible when work sites are not congested and there is easy access for two interacting contractors to work concurrently. In such cases, duration of delays can be minimized. A schematic timescale of this type of call-back and rework is shown in Figure 9.4.

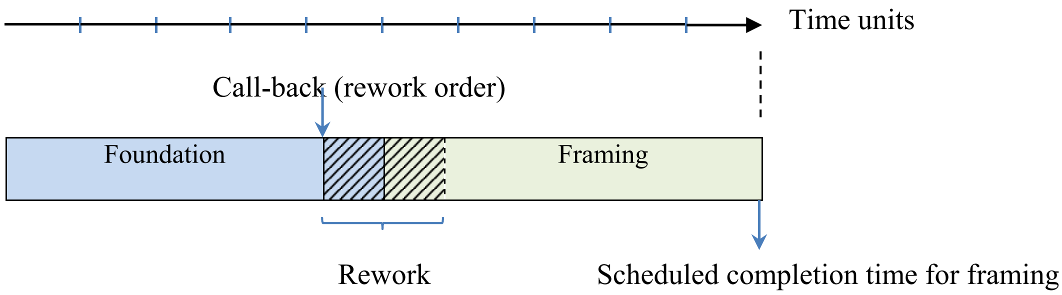


Figure 9.4. Timescale of processes- call-back prior to process completion

When there is no spatial interference, this optimal sequencing can result in timely completion of the processes.

9.5. Framework for the experiments

Previous research has analysed rework as a significant variable in the construction workflow (Love, Holt et al. 2002). However, much of the research has focused on a few construction processes, as noted by Sawhney, Walsh et al. (2009). To address this research gap, the current chapter investigates the effects of call-back timeframes and frequency and length of rework on performance of the whole construction network. Aiming to improve production control strategies, this investigation uses mathematical modelling and Discrete Event Simulation (DES) as the tools for analysis.

The standard practice of production house building in Australia is to subcontract processes to specialized trade contractors. Production data such as process times, delays, rework durations and availability of resources were collected from two volume house builders by conducting numerous site observations. Then the construction model involving 50 contractors responsible for about 100 processes was developed using the same approach as Yu (2011). Twelve production scenarios were analysed in order to investigate compound effects of the rework variables. Frequency and length of rework along with different call-back timeframes were the main analysed rework variables. Both mathematical modelling of individual trade contractors and simulation modelling of the whole construction process were undertaken. The computer simulation was conducted using the ARENA simulation systems. Furthermore, SIMAN simulation coding was used in order to develop a more accurately tailored model of the above mentioned variables. The construction processes were simulated over 1000 working days to allow for the production system to move beyond its transient state. Then outputs were compared and contrasted. Care was taken to introduce as many of the existing details as possible into the experiments.

The use of both DES simulation and mathematical models adds robustness to the present chapter. The results are presented and discussed in the following sections.

9.6. Results and discussion

Data obtained in previous studies showed that rework has a significant impact on construction production performance (Love 2002). To analyse underlying variables of rework, different experiments were designed by varying rework length, rework frequency, and call-back timeframes.

Three call-back timeframes were modelled: early, on time and late rework call-backs. These were combined with different length and frequency of rework. As can be seen in Table 9.1, rework durations and intervals were assumed to be exponentially distributed in order to impose maximum randomness to experiments.

Table 9.1. Rework variables (frequency and length).

Rework type	Rework Intervals (days)	Duration of Rework (days)
Very frequent-Very Short (VF-VS)	Exponential, 7	Exponential, 1
Frequent-Short (F-S)	Exponential, 14	Exponential, 2
Infrequent-Long (I-L)	Exponential, 21	Exponential, 3
Very Infrequent-Very Long (VI-VL)	Exponential, 28	Exponential, 4

Twelve production scenarios were considered by combining three call-back time frames and four frequency and length of rework. It is worth mentioning that availability level and capacity of trade contractors are assumed to be the same. This control on other production parameters, results in a fair comparison of the rework variables in terms of tangible performance measures of the construction system.

The observed trade contractors tend to have different call-back frequency and timeframe. For instance, framing and roofing contractors were most frequent called-back trades. Some other trades experienced late call-backs especially after the occupancy inspections. These call-backs create lengthy rework as trade contractors have already moved their resources to other worksites. Figure 9.5 shows a histogram of observed rework durations.

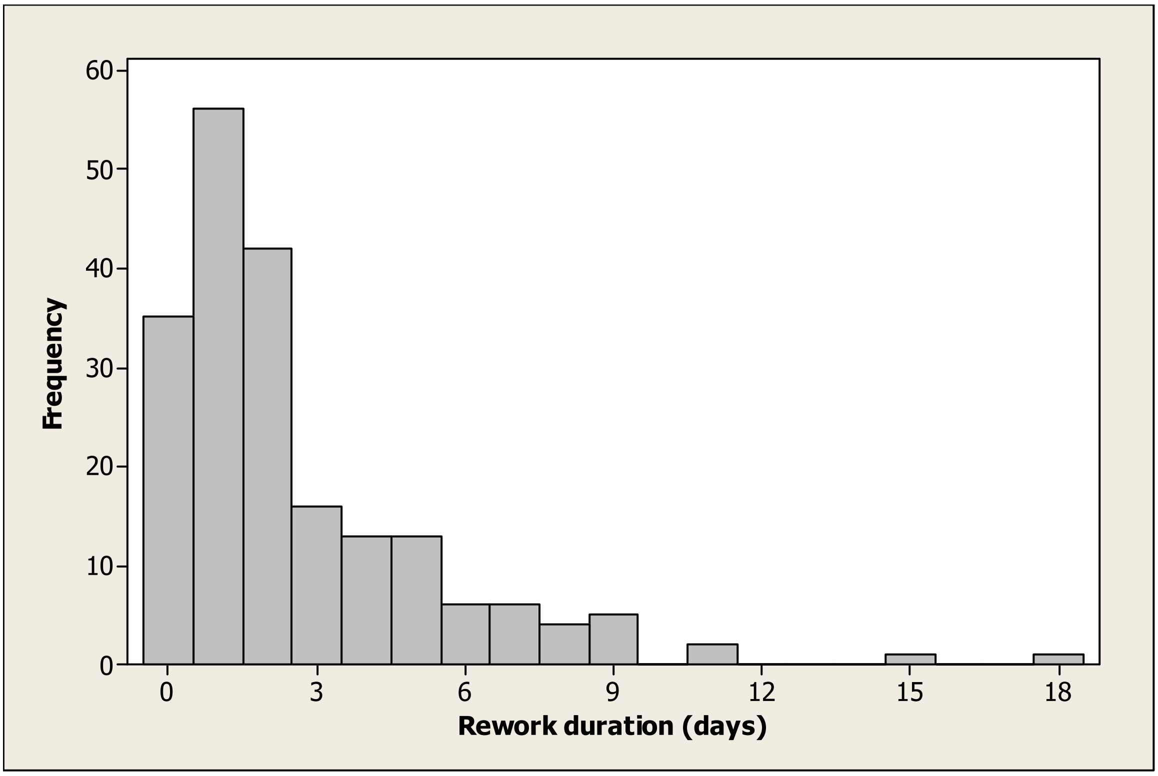


Figure 9.5. Histogram of rework durations

In order to fit the best probability distribution to the rework data, the input analyser tool of *Arena 14.5* was used. Input analyser automatically examines the data against all of the applicable distributions and finds the best fit based on test statistics and minimum square error values. The latter measure is the average of squares of differences between observations and the fitted probability distribution. Table 9.2 orders best fitted distributions based on smallest to largest square errors.

Table 9.2 Quality of fit of probability distributions to the rework data

Order	Probability Distribution	Square error
1	Exponential	0.00275
2	Uniform	0.00363
3	Triangular	0.00436
4	Lognormal	0.00549
5	Normal	0.00666
6	Erlang	0.00847
7	Beta	0.01122
8	Weibull	0.06921
9	Gamma	0.08402

As can be seen, exponential distribution best fits to the empirical data based on the quality of fit measure of square error.

In the house building context, construction supervisors can play a crucial role in preventing long rework. For instance, in the process of concreting the foundation slab some items should be controlled such as rebar size and quantity, overlaps, using barriers between soil and concrete, and using spacers to maintain the minimum concrete cover for the rebar. Such controls could prevent later destructive and non-destructive tests and lengthy rework. In a further step, trade contractors can be trained for early fault-finding in their processes and rectifying them before affecting production processes (Arashpour and Arashpour 2010). This is similar to the paradigm of Total Quality Management (TQM) in manufacturing.

9.6.1. Mathematical modelling

The individual construction processes of concreting the foundation slab was modelled and solved analytically. Process times of slab concreting best fitted the triangular distribution with most likely completion time of seven days. Availability (A) of trade contractors, as the main resource in the volume house building, was computed using mathematical models for production developed by Little (1961) and advanced by Hopp and Spearman (2008):

$$A = \frac{RI}{RI + DOR} \quad (9.1)$$

In Equation (9.1), RI is the rework interval and DOR is the duration of rework.

Rework results in delays and building up queues between processes. The common governing logic for processing jobs in construction queues is First-In-First-Out (FIFO) and its parameters can be computed by the following mathematical equations:

$$t_e = \frac{t}{A} \quad (9.2)$$

$$Q = DOR \times TH \quad (9.3)$$

$$QDR = \frac{1}{t} - TH \quad (9.4)$$

$$QDT = \frac{Q}{QDR} \quad (9.5)$$

In Equations (9.2) to (9.5), t is normal processing time; t_e is effective processing time; Q is queue length after any interruption caused by rework; DOR is duration of rework; TH is throughput rate of a process $(1/t_e)$; QDR is queue depletion rate; and QDT is queue depletion time.

If the next rework occurs before the queue is depleted, it further adds to the number of jobs in queue. The probability (P) of such conflict depends on the process time and queue depletion rate and can be computed by Equation (9.6):

$$P = 1 - e^{-\frac{QDT}{t}} \qquad (9.6)$$

Production parameters in the process of concreting the foundation slab were analytically computed. The results for different frequency and length of rework have been presented in table 9.3.

Table 9.3. Quantitative comparison of production parameters in presence of rework with different frequency and length

Parameters	VF- VS	F- S	I- L	VI- VL
Duration of rework (DOR)- days	Exponential, 1	Exponential, 2	Exponential, 3	Exponential, 4
Availability of trade contractor	87.5%	87.5%	87.5%	87.5%
Throughput rate (TH)- jobs/ day	0.13	0.13	0.13	0.13
Queue length (Q)	0.125	0.250	0.375	0.500
Queue depletion rate (QDR)	0.018	0.018	0.018	0.018
Queue depletion time (QDT)- days	7	14	21	28
Probability- conflict with future rework	63%	86%	95%	98%

The comparison of four rework scenarios in Table 9.3 indicates that job queues are shorter in presence of very frequent but very short (VF-VS) rework, compared to very infrequent but very long (VI-VL) rework. A significant result from mathematical modelling of processes with rework reveals the effect of frequency and length of rework on tangible performance measures. Although longer intervals between rework are commonly preferred by managers, results clearly show that frequent but short weekly rework is better in terms of production parameters. This is in line with previous findings in manufacturing production (Hopp and Spearman 2004). Further, it confirms findings from Tommelein, Riley et al. (1999) that construction project duration can be shortened by decreasing variability in the interlinked network of trades, where the output of predecessors is required by successors to perform their work. In fact, long rework causes work starvations for downstream trade contractors and therefore deviations from project plans.

Results in table 9.3 are controlled for availability of trade contractors and throughput rate in order to have an objective comparison of only rework variables. In order to evaluate the stability of workflow in different production scenarios, variability indicator (VI), introduced in Chapter Four, was used. Equations (9.7) and (9.8) calculate VI when rework occurs during and between construction processes, respectively,

$$VI^2 = 0.1 + A\,(1 - A)\frac{DOR}{t} \tag{9.7}$$

$$VI^2 = \frac{RI(\frac{RI}{t} - 0.5)}{t(RI + DOR)} \tag{9.8}$$

where RI represents the rework interval. Equation (9.7) is for rework during processes and Equation (9.8) is for rework between processes.

Table 9.4 shows the variability indicators (VI) for different timeframes of rework call-backs.

Table 9.4. Quantitative comparison of variability indicator (VI) for different call-back timeframes

Parameters	VF- VS	F- S	I- L	VI- VL
On time early call-backs	0.25	0.43	0.56	0.66
Late call-back	0.34	0.64	0.75	0.85

As the results in Table 9.4 show, VI is smaller when construction supervisors at the site make early or on time call-backs to rectify the faults. Late call-backs, however, dramatically increase VI. This finding places extra emphasis on importance of being proactive for building supervisors in terms of finding incidents of fault and call the responsible trade contractor back before their resources have been released and reengaged in another job. Also the probability of conflict computed by Equation (9.6) shows that construction systems ruled by such management strategy are less likely to face future rework before complete depletion of the previous queue.

This is worth mentioning that there is a striking difference between production in construction and manufacturing as in the latter, rework is commonly regarded as a process, which is usually covered in between other processes and does not interrupt them (Hopp and Spearman 2008). Within the construction context, however, rework usually becomes priority work especially when a mandatory inspection should be passed at major stages of a given project (Sawhney, Walsh et al. 2009).

9.6.2. Simulation modelling

In the second phase, the complete model of production house building, including 50 trade contractors, was simulated over 1000 working days. Figure 9.6 shows the constructed model.

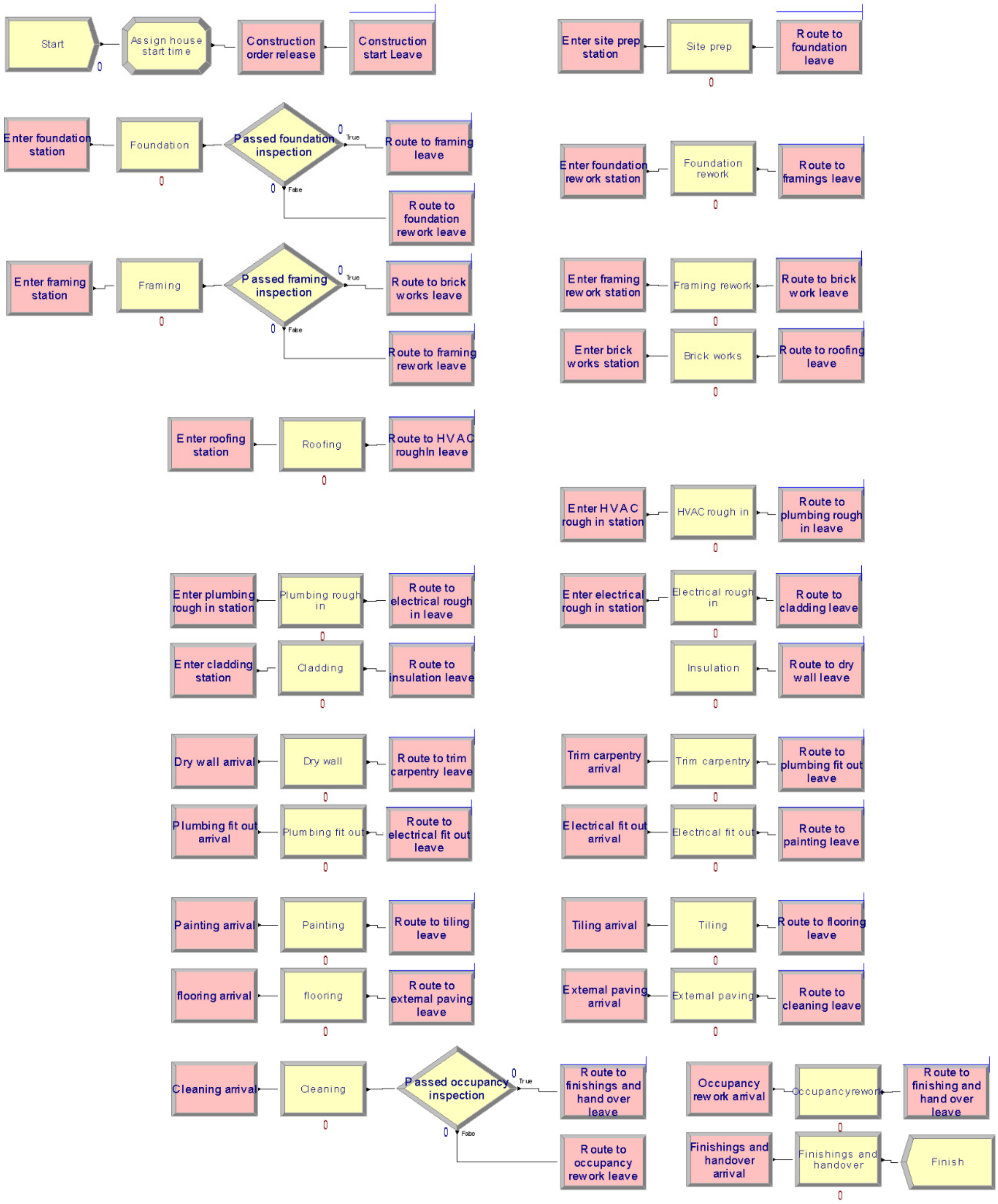


Figure 9.6. House building simulation model

In order to approximate the number of optimal simulation runs for our 12 experiments, the first experiment was simulated for $n_0 = 20$ runs. In this situation, the sample average house completion time was $\bar{X}$ = 275.78 days and the 95% confidence interval for true population mean was 275.78 ± 7 days. This represents 2.5% error in the point estimate of average completion time.

As the half width (h) of the confidence interval for 20 runs was disappointingly high, it was reduced from $h_0 = 7$ days to $h = 3$ days in order to decrease the error in the point estimate of average house completion time to less than 1%. Kelton, Sadowski et al. (2010) suggested that the optimum number of simulation runs based on a pre-specified half width (h) can be approximated by Equation (9.9),

$$n = n_0 \frac{{h_0}^2}{h^2} \qquad (9.9)$$

In Equation (9.9), n_0 is the number of initial simulation runs; h_0 is the half width confidence resultant from initial runs; and h is the desired half width. In the current simulation experiment, $n = 20 \times 7^2/3^2 \approx 100$. Running the simulation experiment for 100 times produced a 95% confidence interval of 274.32 ± 2.53 days. In other words, there is 95% certainty that the true population mean falls between 271.79 and 276.85.

In order to control the statistical sufficiency, experiments 7 and 8 were simulated for 200 and 500 runs. The comparison of results did not reveal any significant difference between errors in the point estimation of average house completion time under 100, 200 and 500 runs. Therefore other experiments were simulated for 100 runs.

A simplified representation of activity cycle diagram for the house building operation is shown in Figure 9. 7. Major processes and resources have been selected for the sake of illustration.

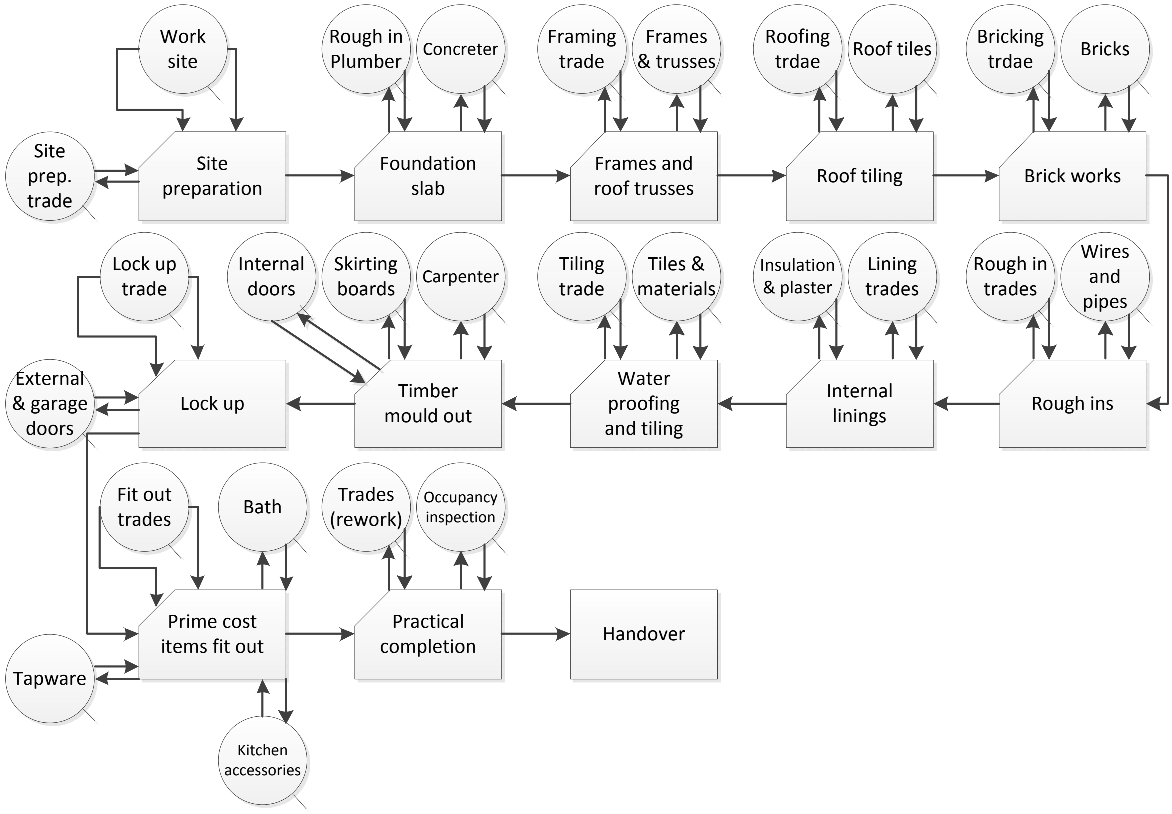


Figure 9.7. Simple representation of activity cycle diagram for house building operation

Understandably, construction networks are too complex to be solved analytically. Although smaller variability indicators for early call-backs showed a better level of productivity in our mathematical modelling, tangible performance measures in volume house building cannot be computed analytically and therefore simulation modelling is required (Henderson, Vaughan et al. 2003). Simulation modelling in this chapter can validate the results of mathematical modelling. Also generalizability of the findings for individual processes to the whole system is investigated.

Flow of work between trade contractors (hand-off) is an important attribute in construction. Workflow analysis reveals output rate of each process that is equal to job arrival rate for next immediate processes. To compute the number of houses under construction (work-in-process inventory), the same technique as that used by Palaniappan, Sawhney et al. (2007) was utilised.

Care was taken to model the effects of different timeframes for rework call-backs on arrival rates of downstream trade contractors. Figure 9.8 shows a snapshot of SIMAN coding window for this purpose.

```
;     Model statements for module:  BasicProcess.Process 2 (Foundation)
;
1$            ASSIGN:        Foundation.NumberIn=Foundation.NumberIn + 1:
                             Foundation.WIP=Foundation.WIP+1;
115$          STACK,         1:Save:NEXT(89$);

89$           QUEUE,         Foundation.Queue;
88$           SEIZE,         2,VA:
                             Foundation contractor,1:NEXT(87$);

87$           DELAY:         Triangular(6,7,9),,VA:NEXT(130$);

130$          ASSIGN:        Foundation.WaitTime=Foundation.WaitTime + Diff.WaitTime;
94$           TALLY:         Foundation.WaitTimePerEntity,Diff.WaitTime,1;
96$           TALLY:         Foundation.TotalTimePerEntity,Diff.StartTime,1;
120$          ASSIGN:        Foundation.VATime=Foundation.VATime + Diff.VATime;
121$          TALLY:         Foundation.VATimePerEntity,Diff.VATime,1;
86$           RELEASE:       Foundation contractor,1;
135$          STACK,         1:Destroy:NEXT(134$);

134$          ASSIGN:        Foundation.NumberOut=Foundation.NumberOut + 1:
                             Foundation.WIP=Foundation.WIP-1:NEXT(2$);


;
;
;     Model statements for module:  BasicProcess.Decide 2 (Passed Foundation inspection)
;
2$            BRANCH,        1:
                             With,(90)/100,137$,Yes:
                             Else,138$,Yes;
137$          ASSIGN:        Passed Foundation inspection.NumberOut True=Passed Foundation inspection.NumberOut True + 1
                             :NEXT(3$);

138$          ASSIGN:        Passed Foundation inspection.NumberOut False=Passed Foundation inspection.NumberOut False + 1
                             :NEXT(4$);


;
;
;     Model statements for module:  BasicProcess.Process 3 (Framing)
;
3$            ASSIGN:        Framing.NumberIn=Framing.NumberIn + 1:
                             Framing.WIP=Framing.WIP+1;
168$          STACK,         1:Save:NEXT(142$);
```

Figure 9.8. SIMAN code window for workflow analysis

Using SIMAN coding, tangible performance measures of the house building project were computed. These include number of house completions over the investigation period, the average number of houses under construction (work-in-process inventory) at all times, and the duration between start and end of processing a home (cycle time= CT). A summary of simulation results over 1000 working days has been presented in table 9.5. It should be noted that detached suburban houses in Australia are not usually constructed in tracts and completion times are generally longer than those of other house building markets, particularly the U.S.

market. In this way, homebuyers sometimes have to spend several months in the preoccupancy period, especially during boom periods when demand overtakes supply.

Table 9.5. Relationship between performance measures and rework variables

Experiment	Rework call-backs	Rework Interval	Duration of rework	Completed homes (No.)	Homes under construction	Average CT (days/home)
1	On-time	Very frequent	Very short	91	34	274
2	On-time	frequent	Short	85	37	295
3	On-time	Infrequent	Long	83	39	312
4	On-time	Very infrequent	Very long	79	41	332
5	Late	Very frequent	Very short	82	39	317
6	Late	frequent	Short	76	42	340
7	Late	Infrequent	Long	74	43	357
8	Late	Very infrequent	Very long	72	44	364
9	Early	Very frequent	Very short	98	31	243
10	Early	frequent	Short	95	33	266
11	Early	Infrequent	Long	90	35	283
12	Early	Very infrequent	Very long	88	37	297

According to table 9.5, the shortest completion time for a house is when early call-backs for rework were made when trade contractors have not released their resources yet (experiment 9). Furthermore, Lower levels of WIP inventory in projects with early call-back for rework resulted in lighter loading on available resources and shorter home completion times. The highest number of 98 house completions was achieved in such situation.

The box and whisker chart in Figure 9.9 illustrates the completion times in different experiments.

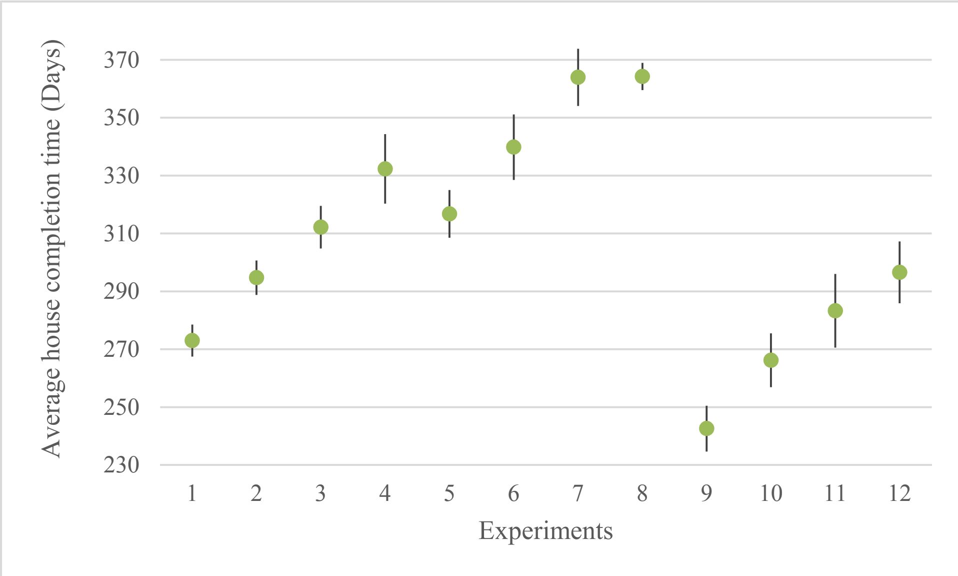


Figure 9.9. Average completion times in 12 experiments

9.6.3. Relationship between rework call-backs and production parameters

Simulation results clearly show that call-back timeframe has a considerable impact on tangible performance measures in house building sector. That is, early call-backs for rework can significantly increase the number of house completions and decrease average completion times. This is consistent with results of mathematical modelling that show a lower variability indicator (VI) for those projects with an early call-back strategy in place, which promises a more stable workflow and therefore higher levels of productivity. In other words, local variation in trade processes, which was analysed in mathematical modelling, can affect the performance of the whole network.

A factorial analysis of variance (ANOVA) was conducted to quantitatively assess the effect of rework variables on house completion times. Results of factorial ANOVA in Table 9.6 clearly show that both call-back timeframes and frequency and length of rework have significant impacts on house completion times (P-value $< \alpha = 0.05$). Furthermore, analysing 1200 completion times (100 runs for each of 12 experiments) showed that there is an interaction between the two independent variables of call-back timeframes and frequency/length of rework.

The F statistic demonstrated that there is significant difference among the means of average house completion times when two independent variables are interacting (see Table 9.6).

Table 9.6. Test of between-subject effects for the dependent variable (average house completion time)

Source	Type III Sum of Squares	Degree of freedom	Mean Square	F Statistics	P-value
Corrected model	293881.065	11	26716.460	165.791	0.000
Intercept	22586198.94	1	22586198.938	140160.668	0.000
Call-back Timeframe (α)	202085.230	2	101042.615	627.029	0.000
Rework Frequency & Duration (β)	88705.391	3	29568.464	183.490	0.001
α × β	3090.444	6	515.074	3.196	0.005
Error	36741.073	1188	161.146		
Total	22916821.08	1200			
Corrected total	330622.138	1199			

Based on the results and by controlling for trade availability levels, those construction processes that experience more frequent but shorter rework can achieve shorter completion times. This is consistent with results of mathematical modelling where job queue length was shorter in such situations and provides a measure of validation. Queue depletion time (QDT) was also shorter than those projects with infrequent but longer rework.

Knowing the significant impact of both rework variables and their interaction on average house completion times, a multiple comparison of variables was then conducted. Scheffe's HSD (honestly significant difference) test was performed in order to compare all possible pairs of means to identify the groups with significant difference. Table 9.7 presents the multiple comparisons of average house completion times in presence of on time, late and early timeframes for rework call-backs.

Table 9.7. Post-hoc test for multiple comparisons of rework timeframes

(I) Call- back timeframe	(J) Call-back timeframe	Mean Difference (I-J)	Standard Error	P-value
On time	Late	-37.4725	1.00714	0.000
	Early	33.5701	1.00714	0.000
Late	On time	37.4725	1.00714	0.000
	Early	71.0426	1.00714	0.000
Early	On time	-33.5701	1.00714	0.000
	Late	-71.0426	1.00714	0.000

As can be seen, different call-backs for rework result in average house completion times that are significantly different (P-value < $\alpha = 0.05$). The biggest difference in average house completion time $(I - J)$ is for late and early call-backs for rework (71.04 days). There are 37.47 days difference in average house completion times when on time and late call-backs are compared. Understandably, $I - J = 71.04 - 37.47 = 33.57$ days when early and on time call-backs are compared. Results in table 9.7 highlight the criticality of call-back timeframes.

A cross-experiment comparison of resource utilisations highlights the significant effect of the rework variables on tangible performance measures (Figure 9.10). For instance, frequent but short rework in experiment 9 along with early call-backs for rework have resulted in the best resource utilisation level comparing with other experiments. Furthermore, the significant difference in house completion times in experiments eight and nine (121 days) can be justified by trade contractor utilisation levels. Conducting a cross-experimental comparison, Figure 9.10 illustrates utilisation levels of 50 trade contractors in experiments eight (worst case) and experiment nine (best case).

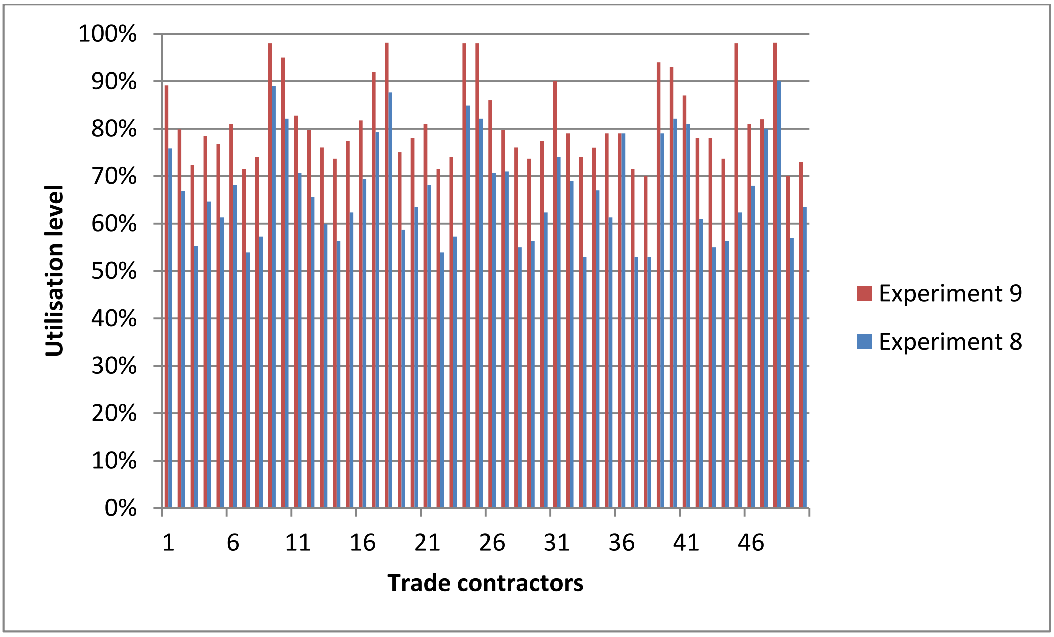


Figure 9.10. Cross-experimental comparison of resource utilisation levels

As can be seen the average utilisation level stood at 81% in experiment nine. Also, the maximum trade contractor utilisation level reached a peak of 98%. In fact, trade contractors were busy most of the time, indicating the more efficient use of available resources. In contrast, infrequent but long rework along with late call-backs for rework can result in idleness of resources. In terms of trade contractor utilisation, experiment eight demonstrates a considerably inferior performance than other experiments. According to Figure 9.10, the average utilisation level of trade contractors was 67% and the minimum utilisation level hit a low of 53%, which means some trade contractors were idle almost half the time.

Overall, late call-backs for rework along with infrequent but lengthy rework significantly downgrade the tangible performance measures of volume house builders. This implies that fault finding at source is the best practice to decrease time overruns caused by rework (Arashpour, Wakefield et al. 2013). Rewarding trade contractors who rectify their own faults before being called back by building supervisors or other trade contractors could prevent later lengthy rework. This is similar to the paradigm of Total Quality Management (TQM) in manufacturing that aims at a continuous quality improvement for processes (Hradesky 1995).

9.7. Chapter summary

Prior work has documented the effects of rework and resultant interruptions on construction projects (Love 2002, Arashpour, Wakefield et al. 2013). However, these studies are limited in application given their use of abstract models to illustrate the effects of rework and consideration of only longer than average duration of processes requiring rework. In order to investigate the interruptions more precisely, this chapter modelled rework in detail, considering its frequency/length and timeframe for the call-backs. Several simulation experiments were designed using data from two production networks that was collected by numerous worksite observations.

Quantitative analysis of mathematical modelling and simulation results showed that production parameters are directly related to rework variables. Infrequent but long rework is found to have more negative effects on completion times compared with frequent but short rework, even if the overall levels of system capacity and resource availability are identical in a controlled experiment. In comparing on time, late, and early call-backs for the responsible trade contractor, the most dramatic adverse effect on production parameters is observed when the contractor is called back late. In this event, the trade contractor has moved their crews to a new worksite. A late call-back for rework interferes with their processes and lengthens the completion times. The findings obtained from mathematical and simulation modelling are consistent and extend those of Dalton, Wakefield et al. (2011) and Hegazy, Said et al. (2011), confirming that rework should be incorporated into production control systems.

9.8. Chapter contributions and future research opportunity

The findings in this chapter clearly show that frequency and duration of rework along with timeframe for call-backs are a significant combination of variables that affect house completion times and the number of completions and therefore should be considered in construction scheduling. The contribution of this chapter to the body of knowledge is to develop an in-depth insight into effects of rework on construction production. This research is generalizable to other sectors of the construction industry to investigate effects of rework on tangible performance measures.

In order to determine the strength of the proposed analytical approach, future research should incorporate more stochastic variables into the model to better reflect the reality in construction sites and enhance the understanding about dynamics and effects of rework on construction production.

10. Chapter Ten – Summary and conclusions

10.1. Introduction

The aim of this research is to improve performance in construction production by designing and testing a production control system that stabilises the workflow, minimises interruptions caused by quality problems, and maximising flexibility in process design. Figure 10.1 illustrates the production control processes involved in the FULFIL system.

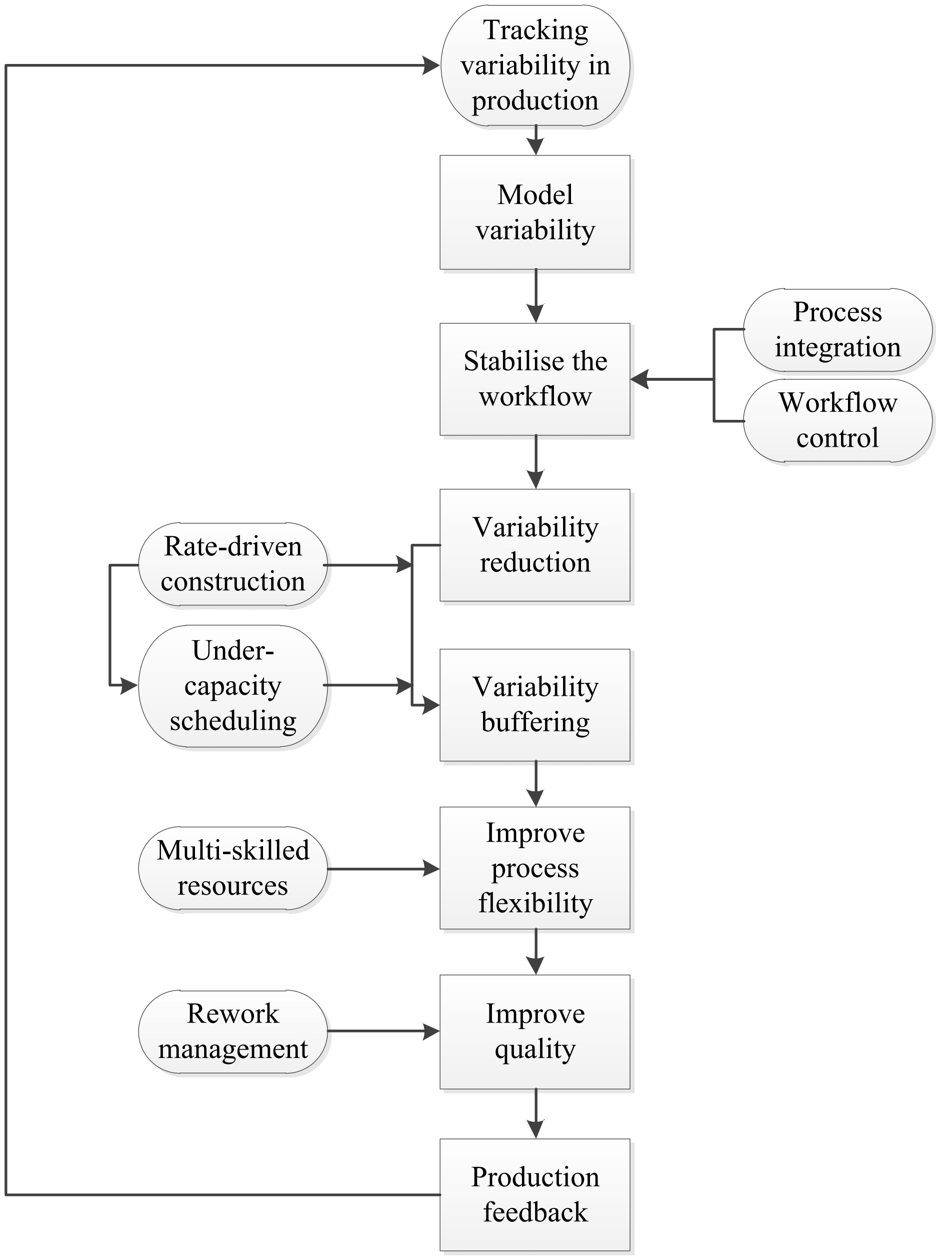


Figure 10.1. Schematic diagram of the FULFIL system of production control

The research aim was translated into seven research objectives that were addressed throughout the thesis. In chapter one it was stated that variability in the workflow is the root cause of poor performance measures such as long completion times, insufficient use of resources, quality problems, and inflexible processes. Chapter two reviewed and compared different modelling strategies to improve performance in construction production. Modelling paradigms in the construction literature for addressing production problems are reviewed in chapter two. Chapter three to nine focused on seven identified objectives in the thesis. Objective one was achieved in

Chapter three, where the first element of the FULFIL system was built to quantify impacts of workflow variability on performance in construction production. Objective two was met in chapter four in which a new approach for modelling workflow variability in construction production networks was proposed. Objectives three, four and five focused on variability management in the FULFIL system. Finally, objectives six and seven were to explore production control strategies that maximise process flexibility and minimise quality-related delays respectively. Figure 10.2 illustrates the seven objectives of the research graphically.

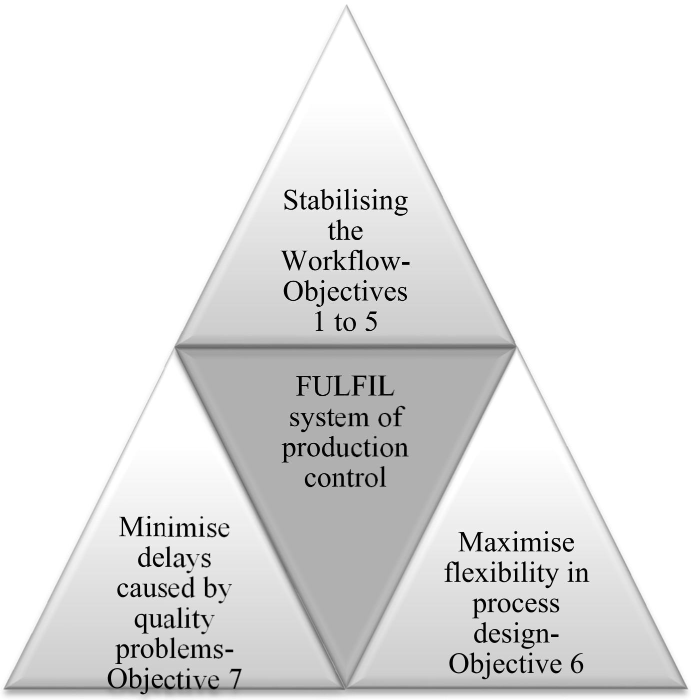


Figure 10.2. Seven objectives of the FULFIL system of production control

Findings about seven objectives of the thesis are summarised in the following section.

10.2. Research contributions

This research makes the following contributions to the body of knowledge:

- The FULFIL system of production control, which is based on queuing theory, TFV theory, factory physics, and theory of constraints, improves the traditional concept of project control. This research takes a holistic approach and analysis in order to stabilise workflow, minimise delays and maximise flexibility.

- This thesis develops a deeper insight into the dynamics of workflow, quality and flexibility, and the impacts on construction plan reliability.
- The current research contributes to the production control theory by:
    - Identifying the superior production control protocols in construction production
    - Optimising the size of capacity buffers in order to improve workflow stability
    - Minimising the delays, especially those caused by quality problems
    - Maximising process design flexibility in construction production

10.3. Conclusions about research objectives

10.3.1. Objective one

To analyse impacts of workflow variability on productivity (FULFIL analysis)

The first objective of the research was addressed in chapter three. In this chapter adverse effects of workflow variability on tangible performance measures at both trade level and project level were analysed. The findings of chapter three were then used in order to propose reactions towards workflow variability in the FULFIL system.

The findings clearly show that construction performance and productivity are very sensitive to the interval of activity starts especially when workflow is subject to variability, caused by factors such as rework. That is, an increase in work quantities at the same time as trade involvement in process variability significantly inflates completion times resulting in workflow congestions and wasted time in the interconnected network of trades.

These findings confirm that performance and productivity in the construction production can be improved through variability reduction and variability buffering approaches. In addition, control of workflow variability can streamline processes within the network of trades, avoiding frequent work overloads or work starvations imposed on trade contractors.

The next objective focuses on exploring a suitable modelling approach towards workflow variability in construction production networks.

10.3.2. Objective two

To establish a tailored modelling approach that precisely quantifies variability in the flow of work (handoffs) amongst specialty contractors

The impacts of workflow variability on construction production were analysed in the previous chapter. However, in order to control the adverse effects of variability, it is first required to establish a modelling approach that is tailored to construction production. Chapter four modelled the variability in the construction production. Trade contractors closely interact in the interconnected network of projects and the departure rate (r_d) of a predecessor is the arrival rate (r_a) for its successor. In order to measure the relative (not absolute) workflow variability, a new indicator was proposed and tested in simulation experiments. Then, results were validated against little's law, which is a basic equation used in manufacturing management.

Numerous experiments were designed by varying the size of capacity buffers between trade contractors, availability of trade contractors, and the intensity of the variability indicator in house building processes. It was found that there are solid relationships between the above mentioned factors and production parameters. These findings confirm that tracing, modelling and addressing sources of variability in construction can lead to achieving optimum performance measures.

The key contribution of the proposed approach is to enable house building networks to precisely model variability and evaluate the long term performance of trade contractors. This paves the way for optimal decision making on variability reduction and variability buffering approaches in the construction production.

Objective three

To explore approaches to stabilising the workflow in construction production

Chapters three and four investigated impacts of workflow variability and proposed a modelling approach to quantify variability. In order to mitigate high levels of variability in construction production and resulting risks, subcontracting has been widely used. While attempts have been made by construction management professionals to improve the situation within the present system configuration, little attention has been paid to stabilise the workflow between interacting trades in order to improve performance metrics.

Chapter five focused on the third research objective by implementing two principles of stabilising the workflow in construction production. The first strategy – limiting the number of jobs under construction– prevented long queues within the network of trade contractors and substantially reduced completion times. The second strategy – employing cross-trained contractors– was found to significantly improve tangible performance measures by means of reducing the number of work starvations/overloads. These initiatives help to better manage the handoffs among trade contractors and reduce the workflow variability. Findings confirm that faster and more predictable construction systems tend to have more simplified configurations.

Implementing such initiatives are more cost effective than adding more resources during the boom periods because efficiency is all about the how of converting WIP inventory to throughput.

Variability reductions caused by stabilising the workflow between trade contractors can result in significant savings in holding cost for capital that is generally borne by clients. The next objective focuses on exploring the implications of variability reduction for productivity improvement in construction.

10.3.3. Objective four

To explore opportunities for variability reduction in construction production

The fourth objective of this research was addressed in chapter six. In particular, strategies such as controlling the work-in-process (CONWIP) have been at the centre of attention. This chapter analysed the theoretical and practical reasons behind efficiency improvements in pull production together with the CONWIP workflow control protocol. Towards this end, both push (due date driven) and pull (rate driven) production in the construction production were analysed and compared.

Based on the results, adopting the pull production control strategy along with maintaining a constant level of work-in-process can significantly improve tangible performance metrics in volume house building. The findings confirm that direct control of the work-in-process inventory is more feasible than indirect control of throughput and capacity estimations in the push environment. Furthermore, results of analytical models and simulation experiments produced several key observations about the superiority of pull production in the real world construction, such as robustness against errors in determining the optimum number of houses under construction. In fact, optimism in estimating production capacity and the desire to yield as much throughput as possible to maximise profit are making push production prone to errors in the control parameters. That is, overestimating the capacity of the trade contractors' network results in more construction starts and can lead to a loss of money and therefore cash flow problems for builders.

The research reported in chapter six builds up on the current body of knowledge by developing an in-depth insight into the pull and push production control strategies. The results have considerable potential to improve construction production management particularly in three key aspects of efficiency, supervision and controllability. This research has a great potential to be generalizable to other sub-sectors of the construction industry.

10.3.4. Objective five

To explore opportunities for variability buffering in construction production

Chapter six documented the effectiveness of pull workflow in improving tangible performance measures in construction projects. Pull systems, however, do not consider due date integrity explicitly and an additional control measure in form of a capacity buffer is required. The fifth research objective was addressed in chapter seven where effects of capacity buffers on production metrics and the optimal size for such a buffer was investigated.

Chapter seven tested a user-friendly framework for finding the optimal capacity buffer that maximises the workflow stability and minimises the probability of late completions. After collecting the historical production data, gross production capacity of the network was calculated by using time series analysis. Then, cost and capacity optimisations were conducted to find the optimal size of the capacity buffer. Following this, results of mathematical modelling were linked to a discrete-event simulation engine and different real-life production scenarios caused by varying stochastic variables of construction production were analysed.

The robustness of the framework in order to improve the workflow stability through establishing a capacity buffer was tested. Findings of this chapter show that an optimal-sized buffer can improve the ability of pull construction systems in maintaining a synchronised production in which output and demand are coordinated. These findings confirm the positive impact of reducing and buffering variability on improving the productivity in construction. In addition, the results show that setting the optimal capacity buffer requires making trade-offs between lost revenue opportunity caused by oversized buffers and late completion costs caused by undersized capacity buffers.

The research conducted in chapter seven contributes to the body of knowledge by developing a deeper understanding of the role of capacity buffers in improving workflow stability in the construction production. The proposed framework is intended to assist builders in finding the most cost-effective way to operate their network of trade contractors.

The next objective focuses on improving the workflow flexibility in the FULFIL system.

10.3.5. Objective six

To explore flexibility improvement opportunities through cross-training the workforce

The sixth research objective was addressed in chapter eight. In the construction management literature, few studies tested the applicability of cross-training strategies in production networks. In order to maximise workflow flexibility in the FULFIL system, chapter eight compares the performance of different cross-training strategies in construction production.

Findings show that when capacity imbalance is the only issue in the system, it can be addressed by borrowing capacity from underutilised trades (non-bottleneck processes) and helping over-utilised trades (bottleneck processes). On the other hand, when processing times are variable, indirect skill chaining is the optimal policy. That is, stations are covered by more than one workforce and capacity is shifted in an indirect path to the bottlenecks. Finally, when both capacity imbalance and variability are significant, the hybrid use of both solutions can best boost the performance measures. The investigation in chapter eight therefore indicates that cross-training can be employed as an effective strategy in order to improve flexibility in the workflow.

Chapter eight contributes to the body of knowledge by expanding the insight into benefits of different cross-training strategies in construction networks. Furthermore, practitioners in the construction industry can use the propositions to make optimal decisions regarding the investment in cross-training.

The next objective of this research focuses on minimising the interruptions caused by quality problems and rework in the FULFIL system.

10.3.6. Objective seven

To explore opportunities for reducing interruptions caused by quality problems and rework.

Chapter eight investigated ways to maximise the workflow flexibility. Chapter nine focuses on the seventh research objective and intends to minimise the adverse effects of rework. Prior work has documented the effects of rework and resultant interruptions on construction projects. However, these studies are limited in application given their use of abstract models to illustrate the effects of rework and consideration of only longer than average duration of processes requiring rework. In order to investigate the interruptions more precisely, chapter nine modelled rework in detail, considering its frequency/length and timeframe for the call-backs. Several simulation experiments were designed using data from two production networks collected by numerous worksite observations.

Quantitative analysis of mathematical modelling and simulation results showed that production parameters are directly related to rework variables. Infrequent but long rework is found to have more negative effects on completion times compared with frequent but short rework, even if the overall levels of system capacity and resource availability are identical in a controlled experiment. In comparing on time, late, and early call-backs for the responsible trade contractor, the most dramatic adverse effect on production parameters is observed when the contractor is called back late. In this event, the trade contractor has moved their crews to a new worksite. A late call-back for rework interferes with their processes and lengthens the completion times. The findings obtained from mathematical and simulation modelling confirm that rework should be incorporated into production control systems.

The findings in chapter nine clearly show that frequency and duration of rework along with timeframe for call-backs are a significant combination of variables that affect house completion times and the number of completions. The contribution of chapter nine to the body of knowledge is to develop an in-depth insight into effects of rework on construction production.

10.4. Limitations

Although using the proposed production control system resulted in significant improvements in performance measures of the investigated case studies, a number of important limitations should be mentioned:

Firstly, using workflow management models in the proposed system was found plausible in the residential construction settings. This sector of the construction industry is very similar to manufacturing and has repetitive production processes. Future work could test applicability of the framework in other construction and infrastructure field activities.

Secondly, adopting analytical models developed in the current research resulted in having optimal (or near optimal) performance measures. However, consideration should be given that these analytical models generally use some simplifying assumptions. For example, they assume that processing times can be represented by a standard statistical distribution, which is not always true in the real-world construction. Such assumptions, however, were not used in the simulation experiments throughout the thesis.

Thirdly, the more than 5000 simulation experiments that were designed and analysed in this research are reflective of typical production scenarios in construction but are not comprehensive of every problem that could happen on worksites. Every construction project has its unique production environment and stochastic variables to be modelled and this should be taken into consideration

10.5. Recommendations for Further Research

This thesis reveals the tip of the iceberg in performance-related issues in construction production. Further research should analyse more management-related variables that affect the performance and identify feasible interventions in order to control their effects on performance and productivity. Furthermore, variability effects on the entire supply chain of construction projects needs more investigation.

Fundamental human behaviour issues such as motivation, learning curve and communication significantly affect the success of any production control system, and require further research in a construction context. In order to determine the strength of the FULFIL system, future research should analyse more what-if scenarios reflecting the reality in construction sites. This will enhance the understanding about dynamics of construction production and develop effective control strategies.

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11. Appendices

11.1. Offsite production of residential units

Figure 11.1. Production of concrete boards

Figure 11.2. Production of steel frames

Figure 11.3. Production of panels

Figure 11.4. Installation of doors and windows

Figure 11.5. Production of roof trusses

Figure 11.6. Loading dock for transportation to the site

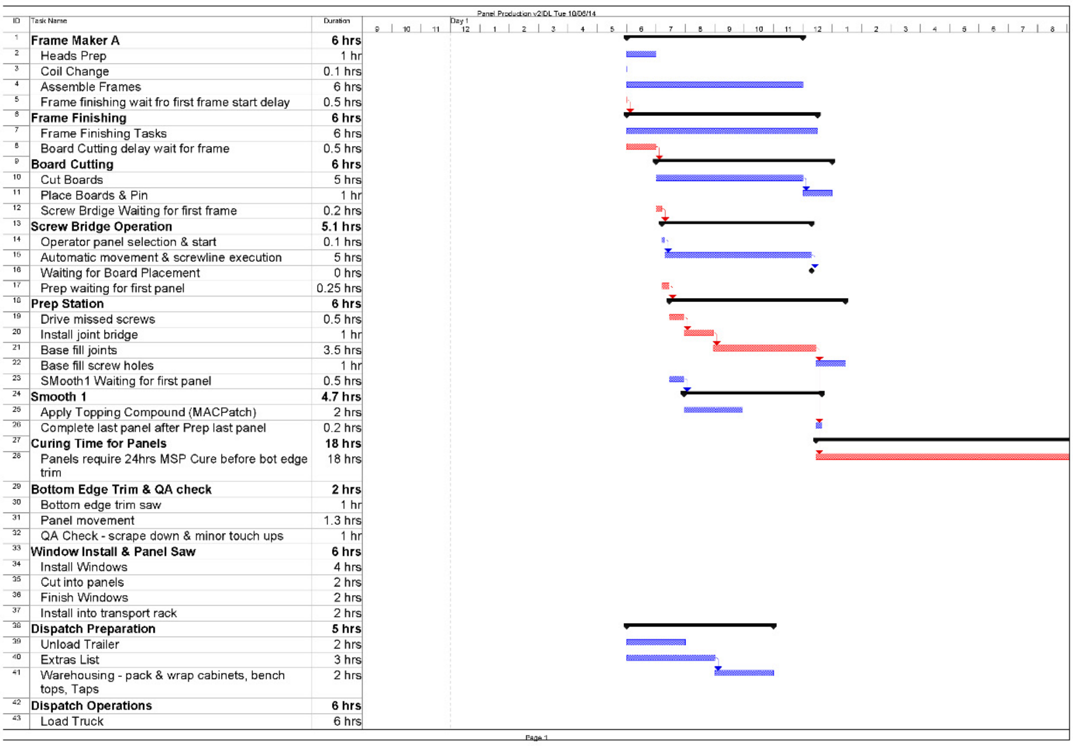

Figure 11.7. Processes involved in the panel production

11.2. Further Reading

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11.3. Research design process

Figure 11.8. Research design illustrated

11.4. Published journal articles

A New Approach for Modelling Variability in Residential Construction Projects

Mehrdad Arashpour, (RMIT University, Australia)
Ron Wakefield, (RMIT University, Australia)
Nick Blismas, (RMIT University, Australia)
Eric Wai Ming Lee, (City University, Hong Kong)

Abstract
The construction industry is plagued by long cycle times caused by variability in the supply chain. Variations or undesirable situations are the result of factors such as non-standard practices, work site accidents, inclement weather conditions and faults in design. This paper uses a new approach for modelling variability in construction by linking relative variability indicators to processes. The mass homebuilding sector was chosen as the scope of the analysis because data is readily available. Numerous simulation experiments were designed by varying size of capacity buffers in front of trade contractors, availability of trade contractors, and level of variability in homebuilding processes. The measurements were shown to lead to an accurate determination of relationships between these factors and production parameters. The variability indicator was found to dramatically affect the tangible performance measures such as home completion rates. This study provides for future analysis of the production homebuilding sector, which may lead to improvements in performance and a faster product delivery to homebuyers.

Keywords: Computer simulaion, Production, Project management, Queuing, Residential construction, Variability in supply chain, Optimim level of work-in-process inventory

Introduction

Simulation of construction processes has received much attention in recent years due to its ability to estimate the behaviour of systems in the presence of variability. Variations or undesirable situations that arise are the result of delays or interruptions in the workflow. Performance measures such as project completion time or resource utilization rates are very sensitive to changes in production variables.

Attention should be paid to address present variability in production systems otherwise the cost will be paid later on in forms of lost output (throughput) rate, wasted capacity, inflated completion (cycle) times, and poor customer service (Arashpour and Arashpour 2012).

Construction processes are different in nature with unequal levels of variability. In residential construction, for instance, an outdoor process such as roofing is more prone to inclement weather conditions comparing with an indoor process such as plumbing. Also, other factors such as accident risks differ from one process to another. In the construction management literature, some researchers have modelled the variability by means of longer mean process times (Walker and Shen 2002, Walsh, et al. 2007, Arashpour, et al. 2013) and some others by assuming a larger variance in process times (Peña-Mora and Dwivedi 2002, Sawhney, et al. 2009, Ghoddousi, et al. 2013). However, the negative influence of variability has been more precisely modelled in other sectors such as manufacturing. Using relative measures of variability have led to a more accurate measurement of system performance in the manufacturing sector (Hopp and Spearman 2008, Jeong, et al. 2011).

Evidence such as lengthened completion times and poor client service particularly during boom periods calls for new approaches for variability modelling in construction projects (Dalton, et al. 2011). On this basis, the present paper uses an innovative approach for modelling variability in residential projects by linking variability indicators to processes. Volume homebuilding was chosen as the scope of this analysis because data is readily available. A two-level hierarchical model was developed to represent the typical production of detached suburban houses in Melbourne, Australia. Several simulation experiments were then conducted by varying: 1. Size of the buffers (queue of jobs to be processed) in front of trade contractors; 2. Level of resource availability; 3. Variability level in the production homebuilding network. In this paper, the effects of variability on the key performance measures such as project completion times and resource utilisation rates are explored.

Review of the Existing Approaches to Model and Address Variability in the Construction Industry

Data obtained in previous studies indicate that variability, which is non-uniformity in building processes, always degrades the performance and productivity measures in construction projects (Moyal 2010, Chia, et al. 2012). Existing strategies are discussed in this section:

A. Using Capacity Buffers against Production Variability

Construction processes are usually defined by the trade contractors who are responsible for them. Buffers between processes can prevent downstream trade contractors to become idle when upstream contractors experience a delay (González, et al. 2011, Koskela and Ballard 2012). Disadvantages of large buffers between interacting trade contractors include a large work-in-process (WIP) inventory and higher costs. In order to investigate this approach to model and address variability, different capacity buffer sizes are modelled and compared in the first and second simulation experiments in the next section.

B. Increasing Resource Availability

Availability of trade contractors can directly affect the completion time of construction processes. During boom periods, homebuilders often use more trade contractors or overtime as buffers against undesirable situations in the work sites (Arashpour, et al. 2012). By authorization of over-time the work capacity increases temporarily and overtakes the demand rate. However, the cycle of over-time would start again by any future randomness in demand or production rate (Hopp and Spearman 2004). Any change in availability of resources has an impact on costs, similar to the crashing concept in project planning. The third simulation experiment in this paper focuses on resource availability.

C. Variability Reduction Approaches

Different approaches are available to reduce the variability level in the mass production homebuilding sector. For example, complications at work sites can be decreased by using modular designs. Furthermore, using prefabrication, modularization and preassembly can dramatically leverage the constructability (Blismas, et al. 2010). Another initiative is to use advanced design and marketing methods, which enables the construction firms to schedule the production in advance (Bouchlaghem, et al. 2005, Veryzer 2005).

Flow-smoothing is another way of reducing variability in the construction environment. Different techniques can be used for this aim such as standardizing construction practices (Carlos, et al. 2002), quality management and reducing rework (Henry 2000), and applications of lean principles in industrialized housing production (Höök and Stehn 2008). Furthermore, variability caused by project-based subcontractors can be decreased by developing long-term business relationships with them. In this way, much of the capacity buffer against variability is carried by subcontractors (Kumaraswamy and Matthews 2000, Greenwood 2001). The variability reduction approach has been modelled and analysed in the fourth simulation experiment.

Research Design

Interconnected work processes are main building blocks of construction projects. They are performed either serially or in parallel until the project is completed. In the first step of this study, process times were plotted for main processes in volume homebuilding projects (see Figure 1). Then, statistical parameters of the data were calculated to perform chi-square check (Halpin and Woodhead 1976). Care was taken to match the process times to the optimum statistical distribution.

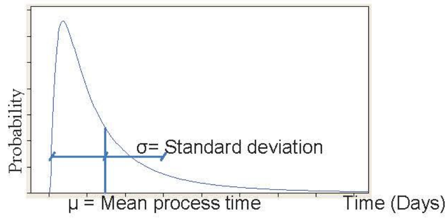

Figure 1 Probability density of cycle times for the construction production system

In the next step, the house building model was developed using similar method to Bashford, et al. (2003). The ARENA simulation software was selected for modelling due to its flexibility in using both ready-to- use constructs and user-written codes by the general-purpose procedural language SIMAN. User-written codes enable precise modelling of unique situations in the production homebuilding sector such as several hand-offs (workflows) among trade contractors. Numerous experiments were designed by varying the size of the capacity buffer between trade contractors, availability level of trade contractors, and level of variability in homebuilding processes.

A new indicator to measure the relative (not absolute) variability were introduced and used in simulation experiments. Then, in order to check the validity of results, they were verified against Little's law, which is a basic equation used in manufacturing management. Finally, conclusions were drawn based on the comparison of results.

Case Study

The typical process of building detached suburban homes in Melbourne, Australia was modelled. Extensive production data are usually kept in volume homebuilding, which makes this sector an ideal subject for investigation. Allocating an ID code to each trade contractor enabled us to trace upstream and downstream processes and analyse the effects of resource availability. In the Australian mass homebuilding sector, all the main building processes are subcontracted to trade contractors. Table 1 shows the list of operations for 20 selected subcontractors.

In production homebuilding, the builder is solely focused on sales and construction management. Subcontractors are in charge of performing construction operations (Walsh, et al. 2004). Due to congestion in work sites, subcontractors are required to finish their job quickly and vacate the workface for the next contractor. The transfers of work among trade contractors is sometimes called 'hand-offs' and becomes complicated by increasing the number of involved trade contractors.

Simulation is a suitable approach to empirical work as it is very costly to play with real systems and examine (pre-test and post-test) their behaviour upon changes in input variables (Fellows and Liu 2008, Martinez 2010). Despite the fact that performance measures in simulated systems involving variability might be subject to error, long simulation runs allow production systems to stabilize and achieve reliable outputs (Hopp and Spearman 2008)[1].

Selected homebuilding elements			
Process	**Subcontractor ID**	**Process**	**Subcontractor ID**
Site preparation	1	Drywall	11
Foundation	2	Trim carpentry	12
Framing	3	Plumbing fit-out	13
Brickworks	4	Electrical fit-out	14
Roofing	5	Painting	15
HVAC rough in	6	Tiling	16
Plumbing rough-in	7	Flooring	17
Electrical rough in	8	External paving	18
Cladding	9	Cleaning	19
Insulation	10	Finishing and handover	20

Table 1 Construction processes and related subcontractors

Variability in Process Times

The mean construction process time (μ) is not fixed and there is always variability around each process. The variability can be caused by several factors such as queuing time to use resources, rework, inclement weather conditions, and accidents on the work site. Both commonly used parameters of mean (μ) and standard deviation (σ) of construction process times reflect absolute variability. However, relative variability is more important in the production process (Hopp, Iravani et al. 2011). As an example, consider a 2 mm dimension error that is not critical in the thickness of foundation slabs. The same error, however, can affect the stability and internal tensions of structural elements if it is a deviation from the vertical access of columns. Therefore, a relative Variability Indicator (VI) can be a very robust parameter in analysing construction processes. We propose VI to be the standard deviation of a given construction process time divided by the mean process time:

$$VI = \frac{\sigma}{\mu}$$

Variability indicator is similar to the coefficient of variation in manufacturing proposed by Hopp and Spearman (2008).The key contribution of the proposed approach is to enable

[1] Some might suggest that the assumptions used to build the model are not supported by the state of the building industry. However, it is worth mentioning that all models are abstractions of reality. While there is a considerable debate about how realistic the assumptions of a model need to be, there is a general agreement on accurate prediction as the major aim of any model. In this way, the validity of assumptions is of the second importance. Friedman (1953) argued that a "useful" theory should be judged not by its descriptive realism but by its simplicity and fruitfulness as an engine of prediction. In other words, the value of a model is an empirical question – how useful it is, and how well it predicts. Therefore, the validity of a model cannot be settled by theoretical arguments but only by empirical investigations.

homebuilders to evaluate the long term performance of trade contractors and consider both mean and standard deviation of process times.

Trade contractors closely interact in the interconnected network of projects. In this way, the departure rate (r_d) of a predecessor is the arrival rate (r_a) for the successor:

r_d (subcontractor #1) = r_a (subcontractor #2)

Figure 2 illustrates how two arbitrary trade contractors are interconnected.

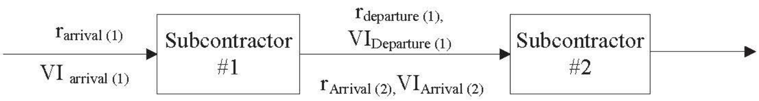

Figure 2 Illustration of the flows of work and variability among trade contractors

Since several interacting contractors are involved in the complex operations of house building, it is logical to consider the maximum randomness for completion times and also job arrival rates. That is, the mean and standard deviation of construction process times can be represented by exponential distribution (VI =1). In this way, once a trade contractor undergoes a very long process time due to bad weather conditions or accidents in the work site, the following trade contractor becomes idle.

Size of the Capacity Buffers in front of Each Trade Contractor

In the absence of variability, the optimum number of houses under construction is equal to the number of trade contractors. This minimises the completion time and keeps every trade contractor busy at all times. This special level of work-in-process (WIP) inventory is called critical WIP (W_0). Upon the presence of variability, average completion time of each house will inflate. To improve the situation, the first two experiments were conducted to find the optimum size of the capacity buffers in order to optimize tangible performance measures: system throughput rate (TH), house completion time (CT), and the number of houses under construction (WIP).In the first experiment, the size of the capacity buffers in front of each trade contractor is quite large and up to 3 houses can stand in a queue to be processed. Exponentially distributed process times introduce the maximum randomness to construction operations.

The second experiment decreased the size of the capacity buffers to only one house. It is worth mentioning that the policy used here is very similar to Kanban squares that are used in manufacturing production lines. At the end of each experiment WIP/W_0 was calculated in order to quantitatively determine how efficient the homebuilding network is working.

Number of Trade Contractors (Resource Availability)

In the third experiment construction processes were accelerated by increasing the resource availability level. Using two dedicated (available for 100 per cent of time) trade contractors for each process resulted the mean process time decreasing to almost half. Similar to the second simulation experiment, a small capacity buffer of one job in front of each trade contractor was used.

Level of Variability in Construction Process Times

In the previous experiments we assumed maximum randomness in the homebuilding network (VI = 1). Variability can be decreased by smoothing the work flow, upgrading the quality of operations in order to minimise the amount of rework, avoid delaying successors, and reducing accidents by means of improved safety measures (Arashpour and Arashpour

2010). The Variability Indicator (VI) of the processes was decreased from 1 to half in the fourth simulation experiment. Trade contractors can be promoted to a new class of variability by reducing the ratio of mean process time to standard deviation over the long term.

Experiments and Output Analysis

Care was taken to model experiments as close as possible to a typical production homebuilding scenario in Melbourne, Australia. For this reason, deterministic distributions for process times and job arrivals were not used. Each experiment was replicated 20 times in order to achieve statistical accuracy in the results. The desired confidence interval was 95% in our study. The simulation experiments were run for 1000 working days. Table 2 illustrates a quantitative comparison of average performance metrics in production runs.

Parameters	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Size of the capacity buffer	3	1	1	1 (houses)
Variability indicator (VI)	1	1	1	0.5
Average throughput rate (TH)	0.55	0.54	0.56	0.58
Resource utilization rate	91.8%	89%	93%	96%
Averagecycle time (CT)	195	135	115	120 (days)
WIP inventory (houses)	36	24	22	23
Per cent of the optimum WIP	180%	122%	180%	116%

Table 2 Performance measures of the volume homebuilding network in the four simulation experiments

In order to cross-check the precision of results and for the sake of verification, the outputs of simulation modelling were compared with an analytical model. Due to the long simulation period, which let the production network reach its steady state, Little's law was selected for verification. Little's law is a queuing formula, which is widely used in manufacturing, in order to predict the performance measures of steady state systems over the long run (Little 2011). It correlates the work-in-process inventory (WIP) to the throughput (TH) rate and completion time (CT):

$$WIP = TH \times CT$$

Experiment	WIP inventory (simulation results)	WIP inventory (analytical results)
1	36	35.7
2	24	24.3
3	22	21.4
4	23	23.2

Table 3 Verification of the outputs (Quantitative comparison of simulation and analytical results)

A two-sample t-test was conducted to verify the results of simulation experiments. No statistically significant difference was found between the performance measures computed by simulation and queuing theory. Table 3 illustrates the results for one of the measures.

As can be seen, running the simulation over the long term caused the system to stabilize and consequently our results complied with Little's law.

Relationship between Capacity Buffer and Production Parameters

In the first experiment and by using a capacity buffer of three houses, the number of homes under construction reached a peak of 36. Consequently, the average cycle time for a single house was inflated to 195 days, as in table 2. This indicates that although capacity buffers prevent downstream contractors from work starvations and idleness, increasing the number of houses under construction results in lengthened completion times. There is a similar situation during construction boom periods, when demand exceeds the capacity of trade networks and houses have to stand in long queues before being processed. Large capacity buffers create big WIP inventories resulting in late completions and decreased service level.

By decreasing the size of capacity buffers in front of trade contractors to 1 house, average completion times decreased dramatically in our second experiment. It is worth mentioning that no extra resources and investment are needed. Improvements in this scenario are the results of changing the control and management policies by limiting the size of capacity buffers. In the second experiment, the number of houses under construction declined to 24, which reduced the average completion time to 135 days (see table 2). The construction output rate (TH) is slightly less than TH in the first production scenario. This is because of occasional job starvations that downstream trade contractors undergo.

Relationship between Resource Availability and Production Parameters

In the third simulation experiment, by increasing the level of resource availability, the average house completion time decreased to 115 days. Furthermore, resource utilization level stood at 93 per cent. This is more than utilization level of 89 per cent in the second experiment where trade contractors occasionally were idle. Although the third experiment achieved the shortest average CT, trade-offs need to be made as reducing the mean value of construction process times here is linked to employing more trade contractors and costs might offset the revenue (unlike the second scenario with no extra costs).

Relationship between VI and Production Parameters: Applications of the New Variability Modelling Approach

The relative variability indicator introduced in this study can differentiate construction processes. Different policies can be used by trade contractors to reduce mean process times and consequently VI. These include avoiding rework by improving quality controls and preventing workflow interruption by improving safety measures.

In the fourth simulation experiment, by reducing the variability indicator to half, a completion time of 120 days was achieved, which is almost identical to the third experiment with its necessary investments. The number of houses under construction is 23, which is very close to the number of involved trade contractors (there is almost no capacity buffer in front of the trades contractors). The work-in-process inventory in this experiment is only 16% more than the optimum critical WIP. In other words, the homebuilding network worked more efficiently comparing with other production experiments (116% of the optimum WIP was the minimum amongst all experiments).

Overall, although there are several opportunities on construction sites to buffer against variability, there are several advantages in attempting to reduce variability. Successful variability reduction strategies, through custom-designed policies, could be implemented in a firm's future projects (Hopp and Spearman 2008). Additionally, improving a specific construction process by finding the source of excess variability would create the mind-set of variability reduction and a culture of continual improvement within the homebuilding networks (Arashpour and Farzanehfar 2011).

Conclusion

Data obtained in previous studies indicate that variability is not accurately modelled and addressed in construction projects. This fact in the mass homebuilding sector results in inflated house completion times, reduction in outputs, and higher capital costs for homebuyers (Bashford, et al. 2005, Arashpour, et al. 2013). In the construction management literature, variability has been mostly modelled by assuming longer process times (pessimistic durations) and/or a larger variance in process times.

To bridge this gap, the present paper has modelled the variability in the production homebuilding sector using an innovative approach. Several experiments were designed by varying the size of the capacity buffers between trade contractors, the availability of trade contractors, and the intensity of the variability indicator in homebuilding processes. We found that there are solid relationships between these factors and production parameters. The findings extend those of Kamat and Martinez (2008) and Li, et al. (2009), confirming that tracing, modelling and addressing sources of variability in construction can lead to achieving optimum performance measures.

The key contribution of the proposed approach is to enable homebuilders to evaluate the long term performance of their trade contractors and decide on the best size of the capacity buffers (queue length of houses to be processed) in front of each trade. Although we investigated the production homebuilding sector, results may be generalized to other sectors within the construction industry.

Future research could include works designed to model variability and investigate its effects on production parameters. The variables within construction projects are numerous and the underlying logic for many system behaviours in the construction sector is still unknown.

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Analysis of Disruptions Caused by Construction Field Rework on Productivity in Residential Projects

Mehrdad Arashpour, S.M.ASCE[1]; Ron Wakefield, M.ASCE[2]; Nick Blismas[3]; and E. W. M. Lee[4]

Abstract: Operational performance in residential construction production systems is assessed based on measures such as average house-completion time, number of houses under construction, lead time, and customer service. These systems, however, are prone to nonuniformity and interruptions caused by a wide range of variables such as inclement weather conditions, accidents at worksites, fluctuations in demand for houses, and rework. The availability and capacity of resources therefore are not the sole measures for evaluating construction production systems capacity, especially when rework is involved. The writers' aim is to investigate the effects of rework timeframe and frequency/length on tangible performance measures. Different call-back timeframes for rework and their impact on house-completion times are modeled and analyzed. Volume home-building was chosen as the industry sector studied in the research reported in this paper because it is a data-rich environment. The writers designed several experiments to model on time, late, and early call-back timeframes in the presence of rework with different length and frequency. Both mathematical modeling and discrete-event simulation were then used to compare and contrast outputs. The measurements showed that the average completion time is shorter in systems interrupted by frequent but short rework. In other words, a smaller downstream buffer between processes is required to avoid work starvation than those systems affected by infrequent but long interruptions. Early call-backs for rework can significantly increase the number of house completions over the long run. This indicates that there is an opportunity for the mass house-building sector to improve work practice and project delivery by effectively managing rework and its related variables. The research reported in this paper builds on the current body-of-knowledge by applying even-flow production theory to the analysis of rework in the residential construction sector, with the intention of ensuring minimal disruption to construction production process and improving productivity. **DOI: 10.1061/(ASCE)CO.1943-7862.0000804.** © *2013 American Society of Civil Engineers.*

Author keywords: Computer simulation; Call-back timeframe; Interruption; Mathematical modeling; Production-planning; Productivity; Queue depletion rate; Rework frequency and duration; Volume house-building; Work flow variability; Quantitative methods.

Introduction

Production cycle time is usually regarded as one of the primary performance measures in projects (Hopp and Spearman 2008). Attempts have been made to optimize both preconstruction and construction phases to shorten completion times. Whereas improvements in both preconstruction and construction phases have been considerable, the construction industry is still regarded as fragmented, with much room for improvement (Ballard and Koskela 2009).

Traditional project-planning uses the critical-path method (CPM) as its primary tool. However, there is a degree of skepticism about the capability of CPM to manage interconnected construction processes (Tommelein et al. 1999). Traditional project-management tools such as CPM-scheduling, earned-value analysis, and cost-estimating fall short when representing interlinked processes in addition to the frequent seize and release of required resources that happens in residential building practice (Bashford et al. 2003).

To address these issues, a production-planning worldview in construction, which is inspired by manufacturing, focuses on not only individual activities but also interlinked resources. This school of thought in construction management has emerged based on the theory of hierarchical construction operations (Halpin and Woodhead 1976). Production management uses discrete-event simulation (DES) for modeling and scheduling. The historical development of construction simulation languages is presented in the Background section of this paper. Over the past decade attempts have been made to develop and test construction production theories in addition to tools (Koskela 2000; Bashford et al. 2003; Salem et al. 2006; Agunbiade et al. 2013).

Although DES-modeling can illustrate interruptions in workflow, improvements are required to distinguish the unique characteristics of interruptions in construction (Ilbeigi and Heravi 2010; Akhavian and Behzadan 2011). In the process of construction, rework can interrupt workflow in different ways. Faults in the work of trade contractors are inspected internally (by the builder's supervisors) or externally (by building surveyors or another third party). The responsible trade-contractor is then called back to rectify the fault. In an ideal situation rework is executed between other construction processes. However, it often becomes priority work that should be undertaken immediately (Sawhney et al. 2009). Furthermore, the length and frequency of rework can affect production performance significantly. Modeling the detailed process of rework

[1]Ph.D. Candidate, School of Property, Construction and Project Management, Royal Melbourne Institute of Technology, Melbourne, VIC 3000, Australia (corresponding author). E-mail: mehrdad.arashpour@rmit.edu.au

[2]Professor of Construction, Head of School of Property, Construction and Project Management, Royal Melbourne Institute of Technology, Melbourne, VIC 3000, Australia. E-mail: ron.wakefield@rmit.edu.au

[3]Associate Professor, School of Property, Construction and Project Management, Royal Melbourne Institute of Technology, Melbourne, VIC 3000, Australia. E-mail: nick.blismas@rmit.edu.au

[4]Assisstant Professor, Dept. of Civil and Architectural Engineering, City Univ. of Hong Kong, Kowloon, Hong Kong, China. E-mail: ericlee@cityu.edu.hk

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in construction, which is analogous to reentrant flow in production systems, has been regarded as difficult in the literature and requiring more research and investigation (Damrianant and Wakefield 2000; Brodetskaia et al. 2013).

To bridge this gap, the research reported in this paper uses an innovative approach tailored to the construction context to model and analyze interruptions of different kinds. Twelve experiments have been designed by varying the following: (1) length of interruptions caused by rework, (2) frequency of rework, and (3) timeframe of call-backs for rework. Both analytical and simulation-modeling have been used to robustly compare and contrast performance measures in the presence of these variables. The research reported in this paper has been conducted in the production-homebuilding sector because mass-homebuilders usually record production data systematically. Although this sector provides the scope for the research reported in this paper, the results are generalizable to other parts of the construction industry.

Background

In this section, previous works that have focused on causes and modeling construction rework are reviewed.

Causes of Construction Rework

There are many discussions of rework in the construction literature. Contributors to rework can be classified into some primary categories, as follows: (1) construction-planning and scheduling, (2) engineering and reviews, (3) human-resource capability, (4) material and equipment supply, and (5) leadership and communication (Fayek et al. 2004). Under such a classification, the root causes of construction field rework involve but are not limited to the following: (1) constructability problems (Feng 2009), (2) unrealistic schedules (Love et al. 2010), (3) changes in project scope (Tuholski 2008), (4) poor document-control (Love et al. 2009), (5) unclear instruction to workers (Thompson and Perry 1992; Arashpour 2012), (6) insufficient skill-levels (Mubarak 2010; Arashpour and Arashpour 2011), (7) lack of safety (Garza et al. 2000; Rajendran et al. 2009), (8) ineffective project-management team (Love et al. 2002; Choi et al. 2011; Arashpour et al. 2012), (9) untimely supply of materials (O'Brien et al. 2006; Hwang et al. 2012; London and Singh 2013), and (10) noncompliance with specifications (Sawhney et al. 2005; Boyd et al. 2013).

Concurrency in the project execution is another contributor to rework. As a short time-to-market is becoming more important in today's construction industry, processes are started before their predecessors are completely finished. Although the so-called management strategy of fast-tracking can help meeting the scheduled time-to-market and therefore greater market share, it can add hidden costs such as rework costs to projects (Salazar-Kish 2001; Mobini et al. 2009; Touran 2010). Project-management tools such as CPM do not capture these and decisions on rework are made based on the managers' judgment. Therefore, finding new approaches to model rework and quantitatively measuring its effect on production parameters are of great importance. Discrete-event simulation is a useful tool for research purposes in the field of construction engineering and management (Martinez 2010).

Modeling of Rework

There are many variables in a construction project that render the models very complex. Simulation-modeling is a useful tool to analyze those construction models that cannot be solved analytically. Simulation is capable of providing information about system behavior under different what-if conditions (AbouRizk et al. 2011). Construction simulation tools have been widely developed and used to model production processes. Fig. 1 shows the evolutionary trend of both general-purpose and domain-specific tools in construction simulation.

These construction simulation languages have been used to model construction processes and relative parameters such as completion time and work-in-process (WIP) inventory (Naresh and Jahren 1995; Kamat and Martinez 2008; González et al. 2009; Behzadan and Kamat 2011). However, the literature is sparse concerning models for construction-management systems that involve consideration of rework caused by design-information changes and quality problems. To mention some examples, Brodetskaia et al. (2013) analyzed reentrant workflow patterns in high-rise residential

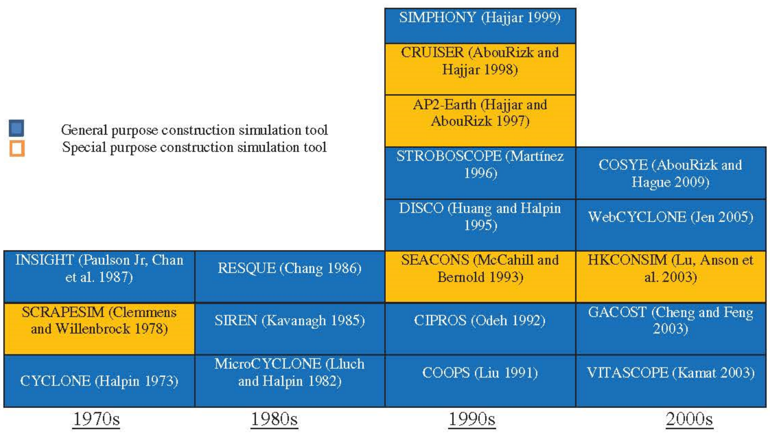

Fig. 1. Historical evolution of construction simulation tools

construction. Some researchers have focused on modeling quality-inspections and their impact on production parameters. For instance, Sawhney et al. (2009) used a composite modeling element in *SIMPHONY* to investigate the impact of inspection pass rate on production output.

Another stream of research adopted mathematical and graphical modeling tools such as Petri nets (PNs) to enhance modeling of construction processes. Petri nets methodology (Petri 1966) facilitates a realistic modeling of delays in the process of construction. For example, Wakefield and Sears (1997) and Sawhney et al. (1999) used Petri nets for simulation and modeling of construction systems. However, only a few studies have investigated the interferences in construction processes using mathematical modeling. Damrianant and Wakefield (2000) and Lu and Ni (2008) used time and color Petri nets to model interruptions in discrete-event systems. In the limited available studies, oversimplistic assumptions such as deterministic process-times and interruption durations have made the models too distant from the reality of construction sites.

Modeling interruptions between and during processes has been regarded as difficult in the literature, requiring more research and investigation (Damrianant and Wakefield 2000; Boukamp and Akinci 2007). The writers aim to bridge this gap.

Modeling of Production-Homebuilding Processes

Construction processes are usually modeled in an interdependent network of predecessors and successors. In the research reported in this paper, the volume of the homebuilding sector was selected as the scope because it is a data-rich environment.

In a common scenario in Australia, mass-homebuilders subcontract up to 100 homebuilding processes to about 50 specialized trade-contractors (Dalton et al. 2011). The common production strategy is make-to-order and there is no building on speculation. Builders' superintendents or construction supervisors are responsible for managing movement-of-work (handoffs) among the trade contractors. Upon completion of a process, trade contractors release their resources and engage them again in the next job. There are two primary requirements for starting a process at its scheduled time, as follows: (1) timely completion of preceding processes, and (2) delivering high-quality work without needing to call-back for rework. As an example, the roofing contractor is dependent on the timeliness and quality of the work of the framing-trade contractor as their predecessor, and a call-back is required upon existence of faults in roof trusses.

Construction processes are resource-constrained and can only be executed upon the availability of resources such as labor, material, and information (Ghoddousi et al. 2013). As an example, Fig. 2 illustrates the process of concreting the foundation slab as part of the production-homebuilding network.

The complete model of production-homebuilding including 50 trade contractors that are responsible for about 100 processes was developed using the same method as Yu (2011). The focus of the model, which is illustrated in a subsequent section on the paper, is on labor and work flows.

Modeling of Interruptions Caused by Rework

In practice, the frequency and duration of rework can affect home-completion times among other production parameters (Sawhney et al. 2009). The timeframe in which rework call-backs occur changes the interruption length and effect. Three possible timeframes for call-backs (rework orders) are discussed in the subsequent sections.

On-Time Call-Backs for Rework before Releasing Resources

The rework is usually ordered when a given construction process has been completed. In Australia, building surveyors carry out four external inspections on major building stages, as follows: (1) foundation, (2) framing, (3) lock-up/waterproofing, and (4) pre-occupancy. Within-organization inspections are conducted by the builders to identify any fault. In the event of a fault, the responsible trade-contractor is called back to rectify it. After the necessary rework has been done, the next trade contractor can then initiate their process. Fig. 3 presents the timescale for foundation rework before the resources have been released.

Since on-time call-back triggers the rework right at the completion time of the process, a later completion time is expected.

Late Call-Backs for Rework after Releasing Resources

Faults are sometimes discovered after initiation of construction processes. In such a situation, call-backs for rework are made after the responsible trade-contractor has left the site and resources have

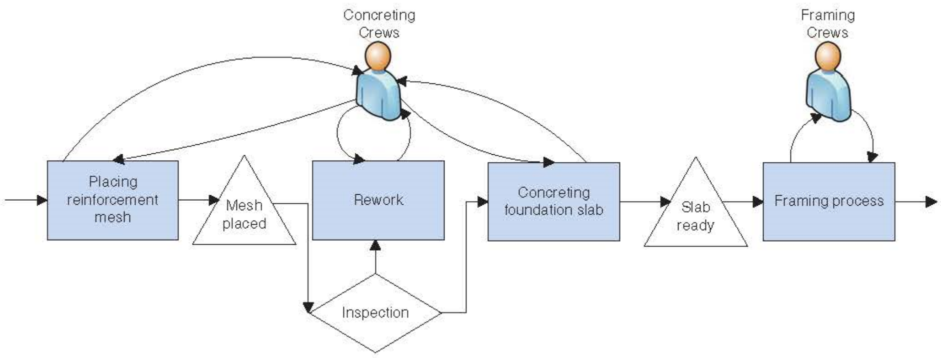

Fig. 2. Process of concreting foundation slab as a part of production-homebuilding

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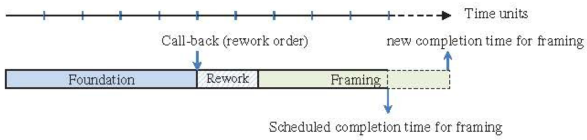

Fig. 3. Timescale for call-back and rework before releasing resources

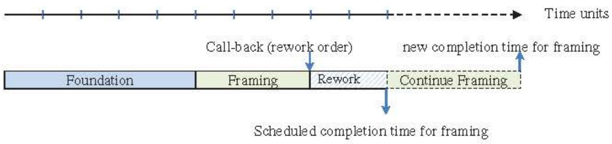

Fig. 4. Timescale for call-back and rework after releasing resources

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been released. In this case, rework becomes priority work for the responsible trade-contractor (Sawhney et al. 2009). This is unique to the construction industry; in manufacturing, for example, rework is commonly regarded as a non-preemptive failure, which can be performed between processes (Hopp et al. 2011). Fig. 4 illustrates the timescale for foundation rework after foundation process resources have been released.

In Fig. 4, the late call-back for rework causes the framing process to be broken into separate parts and therefore has the potential to create long delays. In the research reported in this paper, it is assumed that the framing crew will be available when called back after completion of the foundation rework. In most cases, trade contractors are not dedicated to a single project and will leave to do another job while their processes are interrupted. This may significantly lengthen delays.

Early Call-Backs for Rework Prior to Process Completion: Collaborated Hand-Offs

Close supervision and coordination of construction can result in call-backs for rework being made during the execution of a given process. In this event, the responsible trade-contractor for the rework is able to use already engaged resources to rectify the fault. Upon the availability of sufficient resources, the trade contractor may be able to complete rework using some of the crew while others move to the next job. This is only possible in building detached homes, in which work sites are not congested and there is easy access for two interacting contractors to work concurrently. In this way, delays can be minimized. Fig. 5 shows a schematic timescale of this type of call-back and rework.

When there is no spatial interference, this optimal sequencing can result in timely completion of the processes.

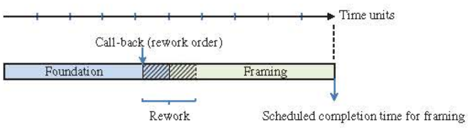

Fig. 5. Timescale of process call-back prior to process completion

Framework for the Experiments

Previous research has analyzed rework as a significant variable in the construction workflow (Love et al. 2002). However, much of the research has focused on a few construction processes, as noted by Sawhney et al. (2009). Therefore, the writers to investigate the effects of call-back timeframes in addition to frequency and length of rework on performance of the entire mass-homebuilding procedure. Opting for a production-management approach, this investigation uses mathematical modeling and DES as the tool for a detailed modeling of volume-homebuilding.

The homebuilding sector was selected as the scope for the research reported in this paper because volume-homebuilders usually keep a good record of production data. The standard practice of production-homebuilding in Australia is to subcontract processes to specialized-trade contractors. Production data such as process times, delays, rework durations, and availability of resources were collected from two mass-homebuilders by numerous site observations. The model of homebuilding involving 50 contractors responsible for about 100 construction processes was then developed using the same approach as Yu (2011). The writers conducted a total of 12 experiments to monitor the compound effect of rework variables. Frequency and length of rework along with different call-back timeframes were investigated. Both mathematical modeling of individual trade-contractors and simulation-modeling of the whole construction process were undertaken. The computer simulation was conducted using *Arena 14.5* simulation systems. The writers also utilized SIMAN simulation coding to develop a more accurately tailored model of the previously noted variables in the home-building context. The processes of mass-homebuilding were simulated over 1,000 working days to allow for the production system to move beyond its transient state. Outputs were then compared and contrasted. Care was taken to introduce as many of the existing details as possible into the experiments.

The use of both DES simulation and mathematical models adds robustness to the research reported in this paper. The results are presented and discussed in the subsequent sections.

Results and Discussion

Data obtained in previous studies showed that rework has a significant impact on construction production performance

Table 1. Rework Variables: Frequency and Length

Rework type	Rework intervals (days)	Duration of rework (days)
Very frequent-very short, VF-VS	Exponential, 7	Exponential, 1
Frequent-short, F-S	Exponential, 14	Exponential, 2
Infrequent-long, I-L	Exponential, 21	Exponential, 3
Very infrequent-very long, VI-VL	Exponential, 28	Exponential, 4

(Dalton et al. 2011). To analyze underlying variables of rework, the writers designed the experiments by varying length, frequency, and call-back timeframes.

Three call-back timeframes for rework call-backs were modeled, as follows: (1) early, (2) on-time, and (3) late. These were combined with different length and frequency of rework. Table 1 shows that rework durations and intervals were assumed to be exponentially distributed to impose maximum randomness to the experiments.

Twelve experiments were constructed by combining three call-back timeframes and four timeframes for frequency and length of rework. The availability level and capacity of trade contractors undergoing all these rework classes are the same. However, tangible performance measures of the homebuilding process are expected to be different.

The observed trade-contractors had different call-back frequency and timeframes. For instance, framing and roofing contractors were the two most frequently called-back trades. Some other trades experienced late call-backs, especially after the occupancy inspections. These call-backs create lengthy rework as trade contractors have already moved their resources to other work sites. Fig. 6 shows a histogram of rework durations.

To fit the best probability distribution to the rework data, the Input Analyzer tool of *Arena 14.5* was used. Input Analyzer automatically examines the data against all of the applicable distributions and finds the best fit based on test statistics and minimum square-error values. The latter measure is the average of the squares of the differences between the observations and the fitted probability distribution. Table 2 orders distributions from the smallest to largest square-error.

An exponential distribution best fits the writers' empirical data based on the quality-of-fit measure of the square-error.

In a homebuilding context, construction supervisors can play a crucial role in preventing long rework. For instance, in the process of concreting the foundation slab the following items should be

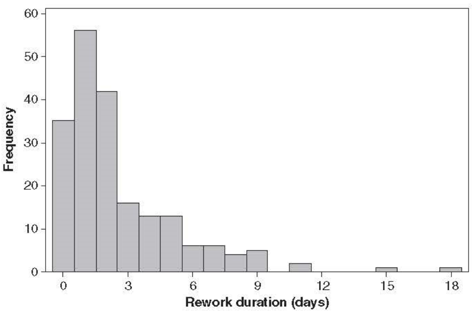

Fig. 6. Histogram of rework durations

Table 2. Quality-of-Fit of Probability Distributions to the Rework Data

Order	Probability distribution	Square error
1	Exponential	0.00275
2	Uniform	0.00363
3	Triangular	0.00436
4	Lognormal	0.00549
5	Normal	0.00666
6	Erlang	0.00847
7	Beta	0.01122
8	Weibull	0.06921
9	Gamma	0.08402

controlled: (1) rebar size and quantity, (2) overlaps, (3) using barriers between the soil and concrete, and (4) using spacers to maintain the minimum concrete cover for the rebar. Such controls could prevent later destructive and nondestructive tests in addition to lengthy rework. In a further step, trade-contractor crews can be trained for early fault-finding in their processes and rectifying them before affecting homebuilding production (Arashpour and Arashpour 2010). This is similar to the paradigm of total quality management (TQM) in manufacturing.

Mathematical Modeling

The individual construction processes of concreting the foundation slab were modeled and solved analytically. Process times of slab-concreting best-fitted the triangular distribution with a most likely completion time of 7 days. Availability A of trade contractors, as the main resource in the volume-homebuilding, was computed using mathematical models for production developed by Little (1961) and advanced by Hopp and Spearman (2008)

$$A = \frac{\mathrm{RI}}{\mathrm{RI} + \mathrm{DOR}} \tag{1}$$

where RI = rework interval; and DOR = duration of rework.

Rework results in delays and building up queues between processes. The common logic of processing jobs in construction queues is first-in-first-out (FIFO) and its parameters can be computed by Eqs. (2)–(5)

$$t_e = \frac{t}{A} \tag{2}$$

$$Q = \mathrm{DOR} \times \mathrm{TH} \tag{3}$$

$$\mathrm{QDR} = \frac{1}{t} - \mathrm{TH} \tag{4}$$

$$\mathrm{QDT} = \frac{Q}{\mathrm{QDR}} \tag{5}$$

t = process time; t_e = effective process time; Q = queue length after any interruption caused by rework; TH = throughput of a process = $1/t_e$; QDR = queue depletion rate; and QDT = queue depletion time.

If the next rework occurs before the queue is depleted, it adds to the queue. The probability P of such a conflict depends on the process time and queue depletion time, and can be computed by Eq. (6)

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Table 3. Quantitative Comparison of Production Parameters in Presence of Rework with Different Frequency and Length

Parameters	VF-VS	F-S	I-L	VI-VL
Duration of rework	Exponential, 1	Exponential, 2	Exponential, 3	Exponential, 4
Availability of contractor (%)	87.5	87.5	87.5	87.5
Throughput rate TH (jobs/day)	0.13	0.13	0.13	0.13
Queue length	0.125	0.25	0.375	0.5
Queue depletion rate	0.018	0.018	0.018	0.018
Queue depletion time (days)	7	14	21	28
Probability of conflict with a future rework (%)	63	86	95	98

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$$P = 1 - e^{\frac{-QDT}{t}} \tag{6}$$

Production parameters in the process of concreting the foundation slab were analytically computed. Table 3 shows the results for different frequency and length of rework.

A significant result from mathematical modeling of processes with rework reveals the effect of frequency and length of rework on tangible performance measures. Although longer intervals between rework are commonly preferable by managers, the results show that frequent but short weekly rework is better in terms of production parameters. The comparison of four cases in Table 3 indicates that job queues are shorter in the presence of very frequent but very short (VF-VS) rework. This is in line with previous findings in production manufacturing research (Hopp and Spearman 2004; Aghajani et al. 2012). It confirms findings from Tommelein et al. (1999) that construction project duration can be shortened by decreasing workflow variability inside the interlinked network of trades, in which the output of predecessors is required by successors to perform their work (parade game). Long rework causes work starvations for downstream trade-contractors and therefore deviations from project plans.

In accordance with the results presented in Table 3, the availability and throughput rate are identical for the experiments. Therefore, these production parameters cannot reflect the effect of different timeframes for rework call-backs. The variability indicator VI is a more useful parameter that evaluates the smoothness of job movements between trade contractors. Readers can refer to Hopp and Spearman (2008) for more information about variability computations. Eqs. (7) and (8) calculate VI when rework occurs during or between construction processes

$$(\mathrm{VI})^2 = 0.1 + A(1-A)\frac{\mathrm{DOR}}{t} \tag{7}$$

$$(\mathrm{VI})^2 = \frac{\mathrm{RI}\left(\frac{\mathrm{RI}}{t} - 0.5\right)}{t(\mathrm{RI} + \mathrm{DOR})} \tag{8}$$

Table 4. Quantitative Comparison of Variability Indicator for Different Call-Back Timeframes

Parameters	VF-VS	F-S	I-L	VI-VL
On time/early call-backs	0.25	0.43	0.56	0.66
Late call-back	0.34	0.64	0.75	0.85

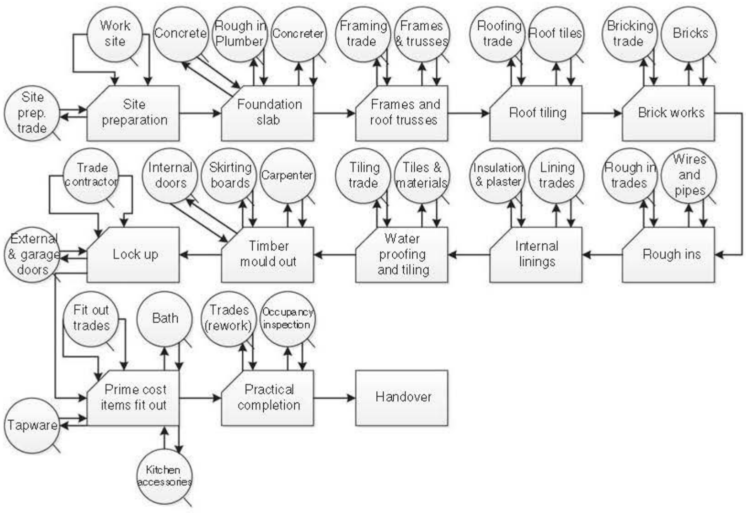

Fig. 7. Simplified representation of activity-cycle diagram for house-building operation

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where RI = rework interval. Eq. (7) is for during processes and Eq. (8) is for between processes.

Table 4 shows the variability indicators VI for different timeframes of rework call-backs.

The results in Table 4 show that VI is smaller when construction supervisors at the site made early or on-time call-backs to rectify the faults. Late call-backs, however, dramatically increased VI. This finding places extra emphasis on the importance of being proactive for building supervisors in terms of finding incidents of fault and calling the responsible trade contractor back before their resources have been released and reengaged to do another job. The probability of conflict computed by Eq. (6) shows that construction systems ruled by such a management strategy are less likely to face future rework before depletion of the previous queue.

There is a striking difference between production construction and manufacturing in this case because in manufacturing rework is traditionally regarded as a process, which always happens between other processes and does not interrupt them (Hopp and Spearman 2008). Within the construction context, rework often becomes priority work, especially when a mandatory inspection should be passed at major stages of a given project (Sawhney et al. 2009).

Simulation Modeling

In the second phase of the research reported in this paper, the complete model of production homebuilding, including about 50 trades, was simulated over 1,000 working days. To approximate the number of required simulation runs for the writers' 12 experiments, the first experiment was simulated for an initial number of simulation runs $N_0 - 20$. In this situation, the sample average house completion time $\bar{X}$ was 275.78 days and the 95% confidence interval for the true population mean was 275.78 ± 7 days. This represents 2.5% error in the point-estimate of the average completion time.

As the half-width h of the confidence interval for 20 runs was disappointingly high, the writers decided to reduce it from $h_0 - 7$ days to $h - 3$ days to decrease the error in the point estimate of the average house completion time to less than 1%. Kelton et al. (2010) suggested that the optimum number of simulation runs based on a prespecified half-width h can be approximated

$$N - N_0 \frac{h_0^2}{h^2} \tag{9}$$

where h_0 = half-width confidence resultant from the initial number of runs; and h = desired half width. In the writers' simulation

```
;[     Model statements for module:  BasicProcess.Process 2 (Foundation)
;
1$            ASSIGN:        Foundation.NumberIn=Foundation.NumberIn + 1:
                             Foundation.WIP=Foundation.WIP+1;
115$          STACK,         1:Save:NEXT(89$);

89$           QUEUE,         Foundation.Queue;
88$           SEIZE,         2,VA:
                             Foundation contractor,1:NEXT(87$);

87$           DELAY:         Triangular(6,7,9),,VA:NEXT(130$);

130$          ASSIGN:        Foundation.WaitTime=Foundation.WaitTime + Diff.WaitTime;
94$           TALLY:         Foundation.WaitTimePerEntity,Diff.WaitTime,1;
96$           TALLY:         Foundation.TotalTimePerEntity,Diff.StartTime,1;
120$          ASSIGN:        Foundation.VATime=Foundation.VATime + Diff.VATime;
121$          TALLY:         Foundation.VATimePerEntity,Diff.VATime,1;
86$           RELEASE:       Foundation contractor,1;
135$          STACK,         1:Destroy:NEXT(134$);

134$          ASSIGN:        Foundation.NumberOut=Foundation.NumberOut + 1:
                             Foundation.WIP=Foundation.WIP-1:NEXT(2$);


;
;
;      Model statements for module:  BasicProcess.Decide 2 (Passed Foundation inspection)
;
2$            BRANCH,        1:
                             With,(90)/100,137$,Yes:
                             Else,138$,Yes;
137$          ASSIGN:        Passed Foundation inspection.NumberOut True=Passed Foundation inspection.NumberOut True + 1
                             :NEXT(3$);

138$          ASSIGN:        Passed Foundation inspection.NumberOut False=Passed Foundation inspection.NumberOut False + 1
                             :NEXT(4$);


;
;
;      Model statements for module:  BasicProcess.Process 3 (Framing)
;
3$            ASSIGN:        Framing.NumberIn=Framing.NumberIn + 1:
                             Framing.WIP=Framing.WIP+1;
168$          STACK,         1:Save:NEXT(142$);
```

Fig. 8. SIMAN code window for workflow analysis

Table 5. Relationship between Performance Measures and Rework Variables

Experiment	Rework call-backs	Rework frequency interval	Duration of rework	Number of completed homes	Homes under construction, work-in-process inventory	Average cycle time (days/home)
1	On-time	Very frequent	Very short	91	34	274
2	On-time	frequent	Short	85	37	295
3	On-time	Infrequent	Long	83	39	312
4	On-time	Very infrequent	Very long	79	41	332
5	Late	Very frequent	Very short	82	39	317
6	Late	frequent	Short	76	42	340
7	Late	Infrequent	Long	74	43	357
8	Late	Very infrequent	Very long	72	44	364
9	Early	Very frequent	Very short	98	31	243
10	Early	frequent	Short	95	33	266
11	Early	Infrequent	Long	90	35	283
12	Early	Very infrequent	Very long	88	37	297

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experiment, $N \approx 20 \times (7^2/3^2) = 100$. Running the simulation experiment 100× produced a 95% confidence interval of 274.32 ± 2.53 days. In other words, there is 95% certainty that the true population mean falls between 271.79 and 276.85.

To control statistical sufficiency, experiments seven and eight were simulated for 200 and 500 runs. A comparison of the results did not reveal any significant difference between errors in the point-estimation of average house-completion time under 100, 200, and 500 runs. Therefore, other experiments were simulated for 100 runs.

Fig. 7 shows a simplified representation of an activity cycle diagram for the house-building operation. Only major processes and resources have been illustrated.

Such a model is too complex to be solved analytically. Although smaller variability indicators for early call-backs showed a better level of productivity in the writers' mathematical modeling, tangible performance measures in volume-homebuilding cannot be computed analytically and therefore simulation modeling is required (Henderson et al. 2003). The objective of simulation modeling in the research reported in this paper is to validate the results of mathematical modeling. Generalizability of the findings for individual processes to the entire system is investigated.

Flow of work between trade contractors (hand-off) is an important attribute in mass-homebuilding. Workflow analysis reveals the output rate of each process that is equal to the job arrival rate for the next immediate processes. To compute the number of houses under construction (work-in-process inventory), the same technique as that used by Palaniappan et al. (2007) was utilized. Care was taken to model the effects of different timeframes for rework call-backs on arrival rates of downstream trade-contractors. Fig. 8 shows a snapshot of a SIMAN coding window for this purpose. The readers can refer to Kelton et al. (2010) and Arashpour et al. (2013a) for additional details.

Using SIMAN coding, tangible performance measures of the homebuilding project were computed. These include the number of house completions over the investigation period, average number of houses under construction (work-in-process inventory) at all times, and duration between start and end of processing a home (where CT = cycle time). Table 5 shows a summary of the simulation results over 1,000 working days. Detached suburban houses in Australia are not usually constructed in tracts and completion times are generally longer than those of other homebuilding markets, particularly the U.S. market. In this way, homebuyers sometimes have to spend several months in the preoccupancy period, especially during boom periods when demand overtakes supply.

The box and whisker chart in Fig. 9 illustrates the completion times in different experiments.

Relationship between Rework Call-Backs and Production Parameters

Simulation results clearly show that call-back timeframe has a considerable impact on tangible performance measures in the homebuilding sector. That is, early call-backs for rework can significantly increase the number of house completions and decrease average completion times. This is consistent with results of mathematical modeling that show a lower variability indicator VI for those projects with an early call-back strategy in place, which promises a smoother movement of jobs between trade contractors and therefore higher levels of productivity. In other words, local variation in trade processes, which was analyzed in mathematical modeling, can affect the performance of the entire network. In accordance with Table 5, the shortest completion time for a house is when early call-backs for rework were made when trade contractors have not released their resources yet (experiment nine). Furthermore, lower levels of WIP inventory in projects with early call-back for rework resulted in lighter loading on available resources and shorter home-completion times. The highest number of 98

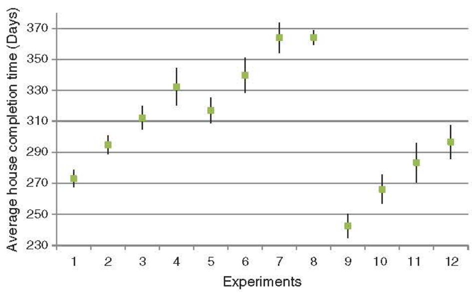

Fig. 9. Average completion times in 12 experiments

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Table 6. Test of Between-Subject Effects for the Dependent Variable, Average House-Completion Time

Source	Type III sum of squares	Degrees of freedom	Mean square	F statistics	P-value
Corrected model	293,881.065	11	26,716.460	165.791	0.000
Intercept	2.258619894×10^7	1	2.2586198938×10^7	140,160.668	0.000
Call-back timeframe α	202,085.230	2	10,1042.615	627.029	0.000
Rework frequency and duration β	88,705.391	3	295,68.464	183.490	0.001
$\alpha \times \beta$	3,090.444	6	515.074	3.196	0.005
Error	36,741.073	1,188	161.146	—	—
Total	2.291682108×10^7	1,200	—	—	—
Corrected total	330,622.138	1,199	—	—	—

house completions was achieved in such situation. This is in line with findings of Barzoki et al. (2011).

A factorial analysis of variance (ANOVA) was conducted to quantitatively assess the effect of rework variables on house-completion times. For ANOVA analysis, F-statistics is computed

$$F - \frac{\text{sum of squares between groups}/\text{DF}_1}{\text{sum of squares within groups}/\text{DF}_2} \tag{10}$$

where DF_1 = between-group degree-of-freedom; and DF_2 = within-group degree-of-freedom.

Results of factorial ANOVA (Table 5) show that both independent variables of call-back timeframe α and frequency/duration of rework β have significant impacts on the dependent variable of house completion times (p-value < 0.05). The comparison of sum-of-square values for α and β suggests that the impact of call-back timeframe on house-completion time is more than rework frequency/duration. Analyzing 1,200 completion times (100 runs for each of the 12 experiments) showed that there is an interaction between the two independent variables of call-back timeframes and frequency/length of rework. Table 6 shows that there is a significant difference among the means of average house-completion times when two independent variables ($\alpha \times \beta$) are interacting.

Having identical levels of availability for trade contractors, those construction processes that experienced more frequent but shorter rework achieved shorter completion times. This is consistent with results of mathematical modeling, in which job queue length was shorter in such situations and therefore provides a measure of validation. Queue depletion time (QDT) was also shorter than those projects with infrequent but longer rework.

Knowing the significant impact of both rework variables and their interaction on average house-completion times, a multiple comparison of variables was then conducted. Scheffe's honestly significant difference (HSD) test was performed to compare all possible pairs of means to identify the groups with significant differences. Table 7 presents the multiple comparisons of average house-completion times in the presence of on-time, late, and early timeframes for rework call-backs.

Table 7. Post-Hoc Test for Multiple Comparisons of Rework Timeframes

Call-back timeframe I	Call-back timeframe J	Mean difference, I–J	Standard error	P-value
On time	Late	−37.4725	1.00714	0.000
	Early	33.5701	1.00714	0.000
Late	On time	37.4725	1.00714	0.000
	Early	71.0426	1.00714	0.000
Early	On time	−33.5701	1.00714	0.000
	Late	−71.0426	1.00714	0.000

The largest mean difference value ($I - J$) belongs to the comparison of average house-completion times for late and early call-backs for rework (71.04 days). The relative p-values confirm the significant difference in house-completion times under different scenarios. The comparison of mean house-completion times, when there are on-time and late rework callbacks, results in 37.47 days of difference. The value of $I - J - 71.04 - 37.47 - 33.57$ days when the mean house-completion times are compared for on-time early call-backs for rework.

Overall, average house-completion times are significantly different when comparing possible pairs of call-back timeframes. Table 6 shows that the independent variable (call-back timeframe) has a significant effect on the dependent variable (average house-completion time). Table 7 confirms that different levels of the independent variable can also significantly affect the dependent variable, highlighting the criticality of call-back timeframes.

A cross-experiment comparison of resource utilizations highlights the significant effect of the rework variables on tangible performance measures (Fig. 10). For instance, frequent but short rework in experiment nine along with early call-backs for rework have resulted in the best resource-utilization level comparing with other experiments. The significant difference in house-completion times in experiments eight and nine (121 days) can be justified by trade contractor utilization-levels. Fig. 10 illustrates the utilization levels of 50 trade contractors in the cross comparison of experiments eight (worst case) and nine (best case).

The average utilization level stood at 81% in experiment nine. The maximum trade-contractor utilization level reached a peak of 98%. Trade contractors were busy most of the time, indicating more efficient use of available resources. In contrast, infrequent but long

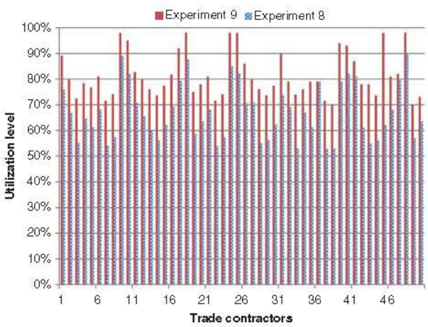

Fig. 10. Cross-experimental comparison of resource utilization levels (experiments eight and nine)

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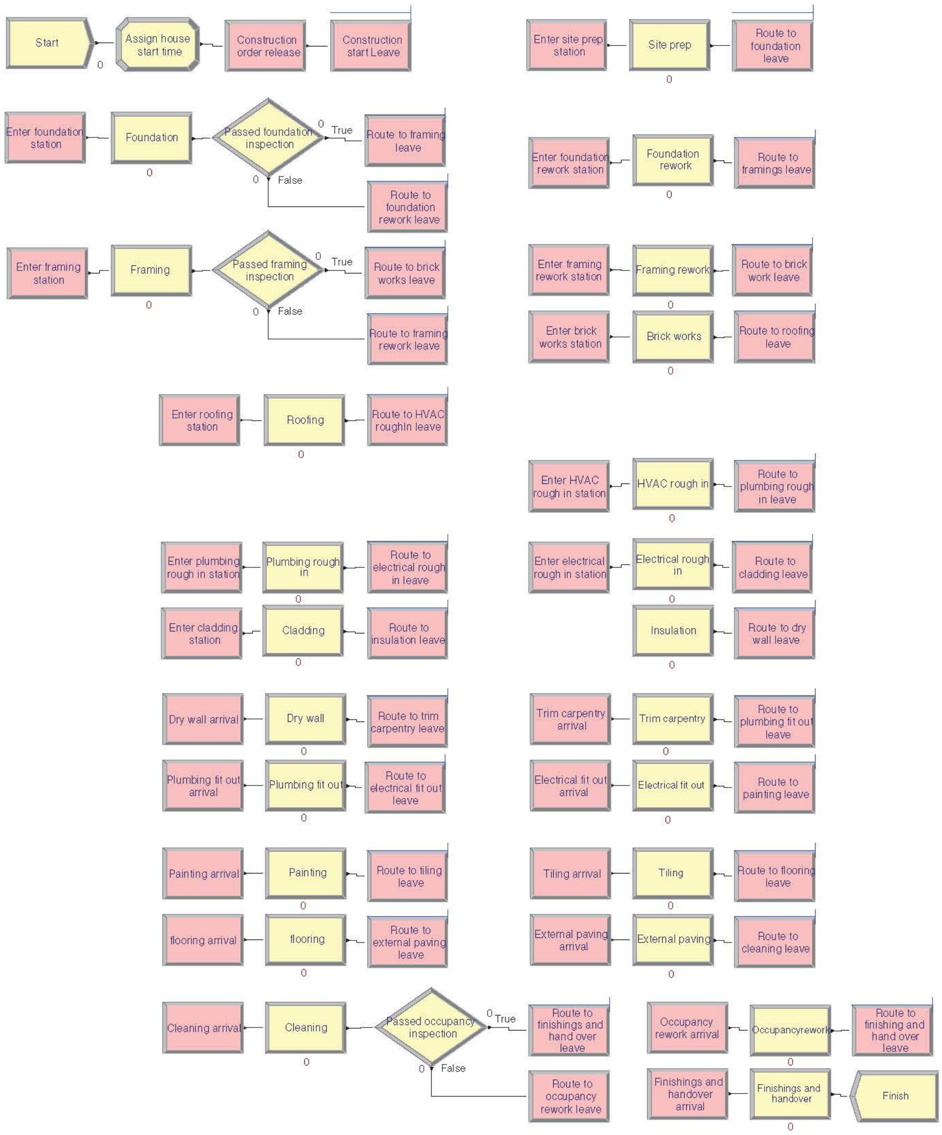

Fig. 11. House-building simulation model

rework along with late call-backs for rework can result in idleness of resources. In terms of trade-contractor utilization, experiment eight demonstrates a considerably poorer performance than other experiments. In accordance with Fig. 10, the average utilization level of trade contractors was 67% and the minimum utilization level hit a low of 53%, which indicates that some trade contractors were idle almost half of the time.

The simulated model of production homebuilding is illustrated in Fig. 11. Overall, late call-backs for rework along with infrequent but lengthy rework significantly downgrade the tangible

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performance measures of mass-homebuilders. This implies that fault-finding at its source is the best practice to decrease time overruns caused by rework (Bayati et al. 2011; Arashpour et al. 2013b). Rewarding trade contractors who rectify their own faults before being called back by building supervisors or other trade contractors could prevent later lengthy rework. This is similar to the paradigm of TQM in manufacturing that aims at a continuous quality-improvement for processes (Hradesky 1995).

Conclusions

Prior work has documented the effects of rework and resultant interruptions on construction projects (Love 2002; Arashpour et al. 2013c). However, these studies are limited in application given their use of abstract models to illustrate the effects of rework and consideration of only longer than average duration of processes requiring rework. To investigate the interruptions more precisely, the research reported in this paper modeled rework in detail, considering its frequency/length and timeframe for the call-back process. Several simulation experiments were designed using data from two homebuilders and collected by numerous worksite observations.

Quantitative analysis of mathematical modeling and simulation results showed that production parameters are directly related to rework variables. Infrequent but long rework has more negative effects on house-completion times compared with frequent but short rework, even if the overall levels of system capacity and resource availability are identical. In comparing on-time, late, and early call-backs for the responsible trade-contractor, the most dramatic adverse effect on production parameters is observed when the contractor is called back late. In this event, the trade contractor has moved their crews to a new worksite. A call-back for rework interferes with their processes and lengthens the house-completion times. The findings obtained from mathematical and simulation modeling are consistent and extend those of Dalton et al. (2011) and Hegazy et al. (2011), confirming that rework should be incorporated into construction-schedule analysis.

Complications caused by rework result in lengthened house-completion times. The writers' findings show that frequency and duration of rework along with timeframe for call-backs are a significant combination of variables that affect house-completion times and the number of completions, and therefore should be considered in construction-scheduling. The contribution of the research reported in this paper to the body-of-knowledge is to develop an in-depth insight into the effects of rework on construction production. This research is generalizable to other sectors of the construction industry to investigate the effects of rework on tangible performance measures. To determine the strength of this analytical approach, future research should incorporate more stochastic variables into the model to better reflect reality in construction sites and further researchers' understanding about the dynamics and effects of rework in construction production.

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A framework for improving workflow stability: Deployment of optimized capacity buffers in a synchronised construction production

Abstract

Construction sites are dynamic environments due to the influence of variables such as changes in design and processes, unsteady demand, and unavailability of trades. These variables adversely affect productivity and can cause an unstable workflow in the network of trade contractors. Previous research on workflow stability in the construction and manufacturing domains has shown the effectiveness of 'pull' production or 'rate driven' construction. Pull systems authorize the start of construction when a job is completed and leaves the trade contractor network. However, the problem with pull systems is that completion dates are not explicitly considered and therefore additional mechanisms are required to ensure the due date integrity. On this basis, the aim of this investigation is to improve the coordination between output and demand using optimal-sized capacity buffers. Towards this aim, production data of two Australian construction companies were collected and analysed. Capacity and cost optimizations were conducted in order to find the optimum buffer that strikes the balance between late completion costs and lost revenue opportunity. Following this, simulation experiments were designed and run in order to analyse different 'what-if' production scenarios. The findings show that capacity buffers enable builders to ensure a desired service level. Size of the capacity buffer is more sensitive to the level of variability in contractor processes than other production variables. This work contributes to the body-of-knowledge by improving production control in construction and deployment of capacity buffers in order to achieve a stable workflow. In addition, construction companies can use the easy-to-use framework tested in this study in order to compute the optimal size for capacity buffers that maximizes profit and prevents late completions.

Keywords: Analytical modeling; Capacity buffer; Construction; Cost optimization; Discrete event simulation; Productivity; Pull workflow; Queue; Time series analysis; Under-capacity planning and scheduling

1. Introduction

Production in dynamic environments such as construction sites are prone to variability caused by external factors such as unsteady demand and also internal factors such as unavailability of resources. This high level of variability results in late completions, decreased output, and lost revenue opportunity for contractors (Lee and Diekmann 2011, Chanmeka, Thomas et al. 2012). Stabilising the workflow in the trade contractor network coordinates the production output and demand and results in a synchronised production. Prior work in the construction literature has focused on designing and implementing pull production systems in order to stabilise the workflow in construction production systems (Im, Han et al. 2009).

The main workflow control mechanism in pull production or rate driven construction is to maintain a constant work-in-process (CONWIP) for the trade network over the production period. The CONWIP protocol enables trade contractors to plan ahead in order to accommodate the demand. Since due dates are not explicitly considered in pull systems, a second control mechanism is required. A capacity buffer or intentional under-capacity scheduling ensures due date integrity in the pull production (Hopp and

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Spearman 2008). However, as stated by González, Alarcón et al. (2011), research on capacity buffers and their effects on tangible performance measures in the construction literature is sparse.

This paper aims to improve the coordination of demand and output of construction using an optimal capacity buffer. In order to achieve this, production data of two Australian construction companies were collected. Then, time series analysis was used to analyse the data and find the production capacity for a future production period. In the next step, capacity and cost optimizations were conducted in order to find the optimal capacity buffer that strikes the balance between late completions and lost revenue opportunity. Finally, results of the mathematical modelling were linked to a discrete event simulation engine where 1200 simulation experiments were designed and run in order to analyse production scenarios in the real-life construction. The findings clearly show that loading the network of trade contractors to full capacity is not always the most profitable policy. In fact, workflow in the network of trade contractors can be stabilised using optimal-sized capacity buffers. Furthermore, the tested and validated framework could be adopted by builders in order to maximise the profit and avoid late completion costs.

2. Background

The prevalence of schedule overruns in the building industry is high (Kim 2009). As the common practice in the industry, risk of late completion is transferred to trade contractors by linking remunerations to the completion of processes. Any remaining risk is then transferred to clients by minimising late completion penalties in the building contractual terms. However, the manufacturing industry has dealt with schedule overruns in a more robust way. Initiatives such as the Toyota Production System (TPS) have tried to continually improve the production environment (Lander and Liker 2007). Furthermore, workflow control protocols such as 'Kanban' attempt to stabilise the workflow in the plant as much as possible and reduce the probability of schedule overruns.

Variability in the production environment will result in late completions regardless of how much the environment has been improved. Variation is the common cause of lack of alignment between demand and production in the construction industry and reducing it should be the top priority to builders (Leaman and Bordass 1999). In the construction industry, there are numerous opportunities to reduce variation. Firstly, variability in building processes can be minimized by adopting flow-smoothing techniques. These include but are not limited to using pull workflow, standardizing construction operations, conducting effective inspections and managing construction rework. Secondly, variation inside the trade contractor network is reduced when builder maintains a long-term working relation with them. In this way, there is guarantee that the builder gets the specialty trades when it needs them. Furthermore, trade contractors will also adopt variability reduction techniques suggested to them by the builder. Overall, reducing variation is pivotal to improving the performance in construction projects over time.

In the following sections, two production planning approaches in the volume house building sector are presented.

2.1. Due date driven house construction

In the traditional construction management approach, building new homes are initiated by signing new sales contracts. In this way, due date integrity can only be achieved when demand is not excessive and

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subcontractors are able to catch up with that. However, during construction boom periods, when demand exceeds supply, this approach is not effective. During boom periods, pushing new jobs into the interconnected network of trade, creates numerous unfinished jobs and workflow congestion. In other words, trade contractors, as the main labour resource in the production network, will be fully utilized and therefore unfinished jobs queue up, waiting for the first resource to become available (Damrianant and Wakefield 2000).

Another problem for achieving due date integrity in push construction is caused by the ubiquity of variability and uncertainty in construction worksites. There are many sources of variability in construction sites such as quality problems and rework (Fayek, Dissanayake et al. 2004, Hegazy and Menesi 2012, Hazini, Dehghan et al. 2013), changes in design and processes (Thomas, Lee et al. 2008), labour productivity (Sonmez 2007, Jarkas 2010, Arashpour, Shabanikia et al. 2012, Dai and Goodrum 2012), contractor's cash flow (Son, Mack et al. 2006, Zayed and Nosair 2006) and undesirable weather conditions (Moselhi, Gong et al. 1997, Shahin, Abourizk et al. 2014). Variability prevents a stable and smooth workflow in the construction network and downgrades the performance measures such as completion time and throughput (Hewage, Gannoruwa et al. 2011).

2.2. Rate driven house construction

In order to rectify the problems of due date driven production, rate driven construction focuses on stability of workflow in the interconnected network of trades and authorises new constructions only when a 'void' in the workflow becomes available upon the completion of a house. In this way, the house production network does not become congested as new starts are only authorised upon the availability of resources. This workflow management strategy, which is very similar to pull production in the manufacturing industry, has been successfully tested in large construction projects (Bashford, Sawhney et al. 2003). Using a capacity buffer in dealing with unscheduled contingencies enables rate driven construction to effectively address variability in construction sites (Arashpour, Wakefield et al. 2013).

Rate driven construction offers significant benefits over due date driven approaches. To mention some benefits, rate driven production systems are more efficient, more robust to control errors, and more supportive of improving quality (Ballard and Koskela 2009). Furthermore, setting an optimal production level (quota) with an appropriately sized capacity buffer can result in coordination between output and demand.

2.3. Using capacity buffers

Traditional methods of project planning and scheduling such as critical path method (CPM) are driven by critical events and do not explicitly consider the production rate of construction networks. New management approaches such as lean construction (Ballard 2000) and the critical chain project management (Goldratt and Cox 2005) propose using capacity buffers in order to address the variability in the production environment. Oversized buffers in construction projects can be wasteful, hinder performance and disrupt the workflow (Horman and Thomas 2005). Undersized buffers, on the other hand, increase the risk of late completions and a poor service level. Performance of a production system is measured by its service level (*SL*) that shows the percentage to which production targets have been achieved (Sezer and Bröchner 2013). In construction projects, *SL* can be defined as the percentage of on-time and on-budget delivery. The current research aims to develop a framework to find optimal-sized capacity buffers.

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The probability of missing the production target should be reasonably low so as to avoid frequent late completions. Consequently, trade-offs need to be made in order to set an optimal production target because high production levels increase the risk of schedule overruns and therefore costs of a late completion. On the other hand, low production levels or under capacity scheduling result in a profit loss because of missing sales opportunities. The research proposes a framework that realizes this trade-off and sets an optimal capacity buffer to improve workflow stability.

3. Research method

3.1. Theoretical basis of the framework

The purpose of this investigation is to find an optimal capacity buffer that maximises the builder profit by stabilising the workflow and minimising late completion costs. Although the theoretical basis of the proposed framework to achieve this purpose has been partly adopted from quota setting research in the manufacturing industry, it has been customised in order to reflect realities in the construction production. High levels of variability, on-going site establishment costs, late completion penalties, and different what-if scenarios in construction are among the factors considered in structuring the framework. Fig. 1 illustrates the proposed framework in this research.

Fig. 1. Framework for improving the workflow stability using an optimized capacity buffer

3.2. Stages of the framework

As can be seen in Fig.1, the framework proposes the following four stages.

Stage 1- Collecting the production data: Important information reflecting the production network capacity should be recorded. Some data reflect the production rate such as number of houses started and completed per month. Furthermore, degree of the workflow stability is reflected by the standard deviation of time between completions. These data points will enter the computations in next stages of the framework.

Stage 2- Computing the gross production capacity of the network: Having collected the actual production data, an average production capacity for the construction network can be computed. Since factors affecting the construction demand, and consequently production, such as house design, market competition, and builder's own marketing are persistent over time, past data can be indicative of future and time series can serve as a suitable tool for finding a gross production capacity (Choy and Ruwanpura 2006, Dissanayake and Fayek 2008, Lee, Fung et al. 2013). This gross production capacity can facilitate management of the construction workflow in the following stages.

Stage 3- Setting an optimal capacity buffer: This part of the framework addresses minimising the probability of late completions by setting a properly sized capacity buffer. Towards this aim, analytical models (see Equations [4] to [6]) are used to formally state the problem of finding the optimal production level and capacity buffer in the construction production. In stage three, two scenarios are analysed. In the first scenario, there is no significant late completion cost for the builder and the major concern is the capacity of the trade contractor network. In the second scenario, late completion costs are significant. Therefore, both capacity and cost optimizations are conducted in order to find the optimal capacity buffer.

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Stage 4- Real time simulation of what-if scenarios: The results of optimization modelling in stage three are linked to a discrete event simulation engine where simulation experiments are designed and run in order to analyse different what-if scenarios in the construction production. Simulation results are recorded in an output data file and can be updated upon the emergence of new production scenarios.

In terms of applying the framework in a construction setting, results of the framework can be automatically used for setting production levels. Actual on-site progress can be used for reconsidering the size of the capacity buffer in a future production period. Iterative processes of the framework can be repeated in short time intervals in order to have a more accurate production control.

4. Results

4.1. Stage 1- Collecting the production data

This research used a systematic approach for data collection that is illustrated in Fig.2.

Fig. 2. Process of data collection and analysis in the current research

In order to conduct the analysis in the second stage of the framework, number of house completions and standard deviation of time between completions were recorded (from January 2011 to December 2013). Production data were collected in standard production units, where a medium-size one-story house was considered as the standard unit. Multi-story/big and small houses were accommodated in the statistical analysis as a multiple/submultiple of the standard production unit (e.g. 1.2x or 0.8x). Number of monthly completions fluctuated between 26 and 54 houses over this production period. Availability of data over long periods of time increases the precision and reliability of predictive models (Blair, Lye et al. 1993).

4.2. Stage 2- Finding the gross production capacity of the trade contractor network

In order to predict the gross production capacity of the trade network in the next production period, four time series forecasting models were used to analyse the data: moving average, single exponential smoothing, double exponential smoothing and the Winter's method. These models predict the gross production capacity by using smoothing constants, α, β and γ. Care was taken in order to automate different stages of the framework and minimise the required user interference. For example, Solver, the internal optimization tool in MS Excel, was used to compute the optimum values for smoothing constants. In order to compare forecasting models, three quantitative measures were used: mean absolute percentage error (MAPE), mean absolute deviation (MAD), and mean square deviation (MSD). These accuracy measures were computed using Eq. 1 to 3.

[1] $$MAPE = \frac{\sum_{t=1}^{n}\left|(x_t - \hat{x}_{t)}/x_t\right|}{n} \times 100$$

[2] $$MAD = \frac{\sum_{t=1}^{n}|x_t - \hat{x}_t|}{n}$$

[3] $$MSD = \frac{\sum_{t=1}^{n}[x_t - \hat{x}_t]^2}{n}$$

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In Equations 1 to 3, x_t is the actual number of monthly completions, $\hat{x}_t$ is the gross capacity forecast and n is the number of observations, which is 36 (months) in this investigation. Each of the accuracy measures computes a numerical score for the difference between actual and fitted values. Smaller values of accuracy measures show a greater forecasting precision. Table 1 presents the accuracy measures for the four predictive models.

Table 1 Three quantitative measures for evaluating the accuracy of gross capacity forecasting

Comparing the measures of precision in table 1, the Winter's method has the smallest accuracy measure values and therefore is the most accurate model to find the gross production capacity of the trade contractor network. This is because the Winter's method captures seasonality and does not overshoot or undershoot the actual production data. Therefore this study uses the Winter's forecasting model and Fig. 3 shows the results of this model for gross capacity analysis over the coming production period.

Fig. 3. Gross production capacity of the trade contractor network (house/month)

A reasonably accurate capacity forecast based on the actual production records enables builders to plan ahead and find the most cost-effective way to operate their production network. For example, as Fig. 3 shows, the gross production capacity forecast for the coming month is equal to 42 houses and therefore the network of trades is orchestrated so that this level of monthly production can be achieved. That is, the monthly productivity mean or gross production capacity of the trade network is set to $\mu = 42$.

Results of the second stage are used to set periodic production targets. Actual on-site progress provides input for reconsidering targets in a future production period. Iterative processes of the framework are repeated in one-month intervals in this research to adjust periodic production targets frequently and have a more accurate production control.

However, actual number of house completions is often less than the gross capacity of the trade network because of the usual contingencies such as unavailability of trade contractors, quality problems and rework, and inclement weather conditions (Arashpour and Arashpour 2010). Actual house completion times are inflated dependent on the presence of variability/uncertainty and so is the risk of undergoing extra costs such as on-going site establishment costs and late completion penalties.

In order to minimise the probability of late completions and stabilise the workflow within the trade contractor network, an optimal-sized capacity buffer is required. In the next sections, two different analytical models are developed to find the optimal size of the capacity buffer in two production scenarios. In the first scenario, late completion costs are not significant for the builder and decision on the size of the capacity buffer is based on the trade network capacity. In the second scenario, however, late completion penalties and on-going site establishment costs are considerable and both capacity and cost optimizations are conducted.

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4.3a. Stage 3- Setting the capacity buffer based on the capacity of the trade contractor network (scenario 1)

In order to find an optimal capacity buffer, this scenario assumes that late completion costs are not significant and decision making is based on the capacity of the trade network. If the agreed completion date is not met, the builder undergoes extra costs associated with a late completion. In this scenario, setting the work-in-process (WIP) level is the most important control measure. In addition, another control measure is also required in order to buffer variability and coordinate the construction output with due dates (Hsie, Chang et al. 2009, Arashpour, Wakefield et al. 2013).

The capacity of a house building network depends on both mean and standard deviation of production. Level of workflow stability in the interconnected network of trades can be reflected by standard deviation of time between completions (Koskela, Sacks et al. 2012). For instance, two builders may have identical production capacity average (μ) but standard deviation of time between completions (σ) is greater in the production network of the first builder (see Fig. 4a). Understandably, the second builder needs a smaller capacity buffer in order to accommodate a similar demand level. In other words, the production predictability of the second builder is more than the first one.

Fig. 4a. Standard deviation of time between completions (Workflow stability) *Fig. 4b.Capacity buffer (92% service level)*

Fig. 4. Production curves of construction networks

Fig. 4b shows that production processes can be approximated by normal distribution with a mean that is equal to the gross production capacity (calculated at stage 2). As illustrated, the network of trade contractors has the gross capacity of completing 42 houses per month. The first control measure in the rate driven (pull) environment controls the work-in-process (WIP) level so that no more than 42 houses are started monthly. The second control measure (capacity buffer) ensures that start and finish of houses are coordinated and production synchronisation is maintained. For example, a capacity buffer of seven houses in Fig. 4b, coordinates the number of starts and completions in 92% of time. In other words, the probability of missing a target house completion (THC) or quota of 35 is only 8% (highlighted area on the graph) and the builder achieves a service level (SL) of 92%. Production curves of builders with lower variability in production have thinner tails. Therefore, probability of missing the target house completion will become less (see Fig. 4a). Assuming a normal distribution for the house building processes, the problem of finding an optimal capacity buffer can be formulated as Eq.4.

[4] $$\Phi\left(\frac{THC-\mu}{\sigma}\right) = 1 - SL$$

In Equation 4, $\Phi(.)$ is the cumulative distribution function (CDF) of production, THC is the target house completion and SL is the service level aimed by the house builder (reliability degree of production). The capacity buffer is equal to $THC - \mu$. The capacity buffer adopts negative values as it downsizes the gross production capacity by a safety factor. For example, suppose that the trade contractor network has the

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gross weekly production capacity of 11 houses with a standard deviation of two. If the desired service level is 85%, the model expressed by Equation 4 will return a target house completion (THC) of 9. Therefore, the capacity buffer is equal to (-2) houses or 18% of the gross production capacity. In other words, by adopting this capacity buffer, the builder will be able to coordinate dates of house start and finish and synchronise production in 85% of time. It is worth mentioning that all computations can be automated using built-in functions in standard statistical packages or MS Excel. For example, in order to return the standard normal distribution, $NORM.S.DIST(.)$ in Excel 2010 and $PHI(.)$ function in Excel 2013 were used.

Table 2 presents THC values for different service levels of 85, 90 and 95%. The size of the capacity buffer is equal to $THC - \mu$ in each construction production scenario.

Table 2 Capacity buffer in 18 production scenarios with different service levels

As can be seen in table 2, larger values of gross production capacity return higher THC. However, THC is decreased by either increasing the standard deviation of time between completions or the desired service level. These results are in line with those of Han, Hong et al. (2011), highlighting the importance of variability buffering in construction processes, especially when higher service levels are desired.

Fig. 5 plots increasing size of the capacity buffers against standard deviations of time between completions, which measures the level of workflow stability.

Fig. 5. Upward trend in the size of the capacity buffer resulted by increasing the standard deviation of time between completions

The linear relationship between the level of workflow stability and the size of capacity buffers is the output of the optimisation model expressed by Equation 4. A more realistic non-linear relationship that is plotted by the outputs of the fourth stage of the framework will be illustrated in Fig. 8b. The model expressed by Equation 4 can be used when capacity of the trade network is the main independent variable affecting the construction production. However, upon the existence of significant late completion costs, this factor should also enter the decision making process on the capacity buffer. In such situations, builders need to consider the trade-off between a bigger capacity buffer, which imposes the lost revenue opportunity, and a smaller buffer, which increases the late completion costs. The model developed in the next section, realizes this trade-off and optimizes the size of the capacity buffer accordingly.

4.3b. Stage 3- Setting the optimal size of capacity buffers based on both production capacity and late completion costs (scenario 2)

In order to find an optimal size for capacity buffers, major costs associated to a late completion should be considered and decision making is based on both these costs and capacity of the trade network.

In order to assist developing a specific model for setting the optimal capacity buffer, the gross production capacity was computed in the second stage of the framework, which is equal to 42 houses per month or

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almost 10 houses per week. If agreed completion dates are not met, builders have to pay extra costs of on-going site establishment and late completion penalties, based on the house building contract. Consider the total cost of late completion (C_{LC}) to be \$300 per week for each house. So for a builder with 10 houses under construction, $C_{LC} = \$3000$ for a week of delay in completion.

Let the net profit of the builder per house be 'e' and the total expected earnings (net revenue minus expected C_{LC}) be denoted by 'E'. In this way, the problem of finding an optimal capacity buffer can be formulated as Equation [5].

[5] $$\max_{THC} E = e \times THC - C_{LC} \times p\ (late\ completion)$$

In Equation [5], 'p' is the probability of having a late completion and size of the capacity buffer is equal to $THC - \mu$. The optimization problem is to find an optimal buffer that strikes the economic balance. While increasing buffer size affects the objective function by causing lost sales, decreasing buffer size affects the objective function by increasing the probability of late completions and associated costs. Assuming a normal distribution for production with mean μ and standard deviation σ, the capacity buffer can be expressed as $THC - \mu = -m\sigma$. Now the decision variable becomes m and we need to find out how many standard deviations below μ the capacity buffer should cover. In a similar approach to Hopp, Spearman et al. (1993), the problem was formulated as Equation [6].

[6] $$\max_{THC} E = e(\mu - m\sigma) - C_{LC} \times p\,[1 - \Phi(m)]$$

In Equation 6, $\Phi(.)$ represents the cumulative distribution function of production. A unique solution to Equation 6 can be yielded by differentiating the objective and setting it equal to zero,

[7] $$m^* = \left[2\ln\left(\frac{C_{LC}}{\sqrt{2\pi}\sigma e}\right)\right]^{1/2}$$

The optimal value of m in Equation 7 is used to compute the optimal capacity buffer size.

[8] $$THC^* - \mu = -m^* \times \sigma$$

Equation 8 shows that both gross capacity mean and standard deviation of time between completions affect the size of capacity buffer. For example, in a case in which the net profit for building a unit is \$43500 and it takes 6 months to complete the unit, the potential weekly profit of the builder will be \$1670. Assuming the sum of site establishment costs and late completion penalties to be \$400 per week, the total C_{LC} will be \$4000 for 10 units under construction. Plugging these values into the above model returns the optimal THC or production quota of 8.0 and optimal capacity buffer of (-2) houses. This capacity buffer, which is equal to 20% of the gross production capacity, can maximise the profit of the builder in this production scenario.

Table 3 shows how these two variables change the house completion target (THC) and consequently the capacity buffer size. As stated earlier, all computations were automated using built-in functions and the internal optimization tool in MS Excel.

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Table 3. Capacity buffer in 12 production scenarios with different late completion costs

Results in table 3 can be used to find the optimal capacity buffer. For example, in a case where the trade contractor network has a gross production capacity of 10 houses per week with a standard deviation of one house and weekly cost of late completion is \$400, the model returns a THC equal to 8.4. This capacity is equal to 16% of the gross production capacity of the trade network.

Results of the optimization model show that increasing the standard deviation of production and costs of late completion (C_{LC}) decreases the target house completion or production quota. This is consistent with findings of Georgy (2008), indicating the impact of variability in production on the workflow stability and required capacity buffers. In the next phase of the framework, comprehensive models with more stochastic variables can be analysed using Monte Carlo simulation.

4.4. Stage 4- Real-time simulation of what-if scenarios

Data obtained in previous studies has shown that variability in the processes of trade contractors results in a reduced throughput, low resource utilisation levels and a higher allocation of overheads (Tommelein, Riley et al. 1999). Construction sites are dynamic environments and production in such an environment is subject to numerous nondeterministic variables. In order to conduct a real-time analysis of these stochastic variables, simulation experiments were designed and run as construction projects are not appropriate laboratories for multiple replications in quantitative studies (AbouRizk, Halpin et al. 2011).

Using the collected production data from the two construction companies, a total of 1200 simulation experiments were designed. Different variables were used in the models, including five gross production capacities, six standard deviations of time between completions, four service levels and 10 values for late completion costs. The project workflow was simulated using the ARENA discrete-event simulation software. Interested readers can refer to Arashpour, Wakefield et al. (2014) for a more detailed treatment of the modelling approach. Input variables to simulation models were automatically read from an excel spread sheet that contained the collected data.

Histograms of the collected data points were plotted and best-matching probability distributions were fit to the data. Selected probability distributions were evaluated against three goodness-of-fit tests; Anderson–Darling test, Kolmogorov–Smirnov test, and Chi–Square test. Care was taken in order to construct the simulation model so that it reflects the reality in the real-world construction setting. For example, the traditional Poisson process with exponential inter-arrival time was not used for representing random arrival of jobs to the construction network. As illustrated in Fig. 6, the three goodness-of-fit tests suggest that random arrivals can best be represented by Gamma distribution with the shape factor of 2.533 and scale factor of 5.999.

Fig. 6. Histogram of collected data on inter-arrival times

Best-fitting probability distributions were used in order to feed the simulation model with the knowledge extracted from the empirical production data.

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5. Empirical analysis

5.1. Impact of service level on the size of the capacity buffer

Based on the simulation results, Fig. 7 shows increasing the desired service level (SL) inflates the size of capacity buffer nonlinearly and consequently squeezes the level of target house completion (THC).

Fig. 7. Optimal size of the capacity buffer in simulation experiments (enforcing a growing service level)

As Fig.7 reveals, increasing the service level decreases the level of target house completion (THC) in a nonlinear trend. That is, if the builder tends to have a reliable production and achieve on time completions, a conservative THC level should be maintained. This is consistent with the optimization results in the previous section (table 2) and provides a measure of validation. Furthermore, it extends finding of Arashpour, Wakefield et al. (2013), indicating that loading operations to the full capacity is not necessarily the best production strategy and a decent-sized capacity buffer will help both homebuilders by avoiding late completion costs and homebuyers by shortening the preoccupancy period.

5.2. Impacts of the gross production capacity and workflow stability on the size of the capacity buffer

Optimization models in the previous stage of the framework revealed that size of the capacity buffer is dependent on the average production capacity and standard deviation of time between completions. In a controlled simulation experiment, the gross production capacity fluctuated between 400 and 600 houses per year while the standard deviation of time between completions was controlled. Results of running the simulation experiment have been illustrated in Fig. 8a.

Fig. 8a. *Target house completion (controlled for production variability)* ***Fig. 8b.*** *Capacity buffer vs. production variability*

Fig. 8. Simulation results on Target house completion and size of the capacity buffer

As can be seen in Fig. 8a, increasing the gross production capacity results in a growing level of target house completion (THC). However, it is controlling the standard deviation of time between completions that keeps the size of the capacity buffer constant. It is worth mentioning that having a stable workflow by fully controlling the variability over a long-term production is a difficult task, which is hardly achievable in construction sites. Therefore, the production variability should also be taken into consideration before loading the network of trades to full capacity and starting as many new constructions as possible, which is a common approach in the house building environment (Arashpour and Arashpour 2011).

Given the presence of variability, the number of unfinished jobs grows exponentially and the production system soon becomes unstable. Fig. 8b plots the increasing size of the capacity buffer against standard deviations of time between completions, which measure the workflow stability. As can be seen in this figure, construction production networks with more stable workflows require smaller capacity buffers. That is, the builder is able to meet the production target easier and consequently a higher service level is

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achievable. The striking difference between Fig. 8a and Fig. 8b highlights the high sensitivity of the capacity buffer size to the level of workflow stability. This is in line with the findings of González, Alarcón et al. (2011), indicating that focusing solely on capacity of the trade network can be misleading for builders and causes a lack of coordination between construction output and start. In fact, without the aid of an optimal capacity buffer, target house completion (THC) and expected profit will decline over the long-term production. This is consistent with the results of running optimization models in table 3 and validates them.

6. Limitations

Although using the proposed framework resulted in significant improvements in performance measures of the two case studies, a number of important limitations should be mentioned:

Firstly, using predictive models in the proposed framework was found plausible in the residential construction settings. This sector of the construction industry is very similar to manufacturing and future production can be predicted by analysing the past performance. Future work could test applicability of the framework in other construction subsectors.

Secondly, adopting two optimization models developed in the current research resulted in finding optimal (or near optimal) capacity buffers for the two case studies. However, this should be taken into consideration that these models are simplified to be easily used. For example, they assume that processing times are normally distributed, which is not always true in the real-world construction. Such assumptions, however, were not used in the simulation experiments at the fourth stage of the framework.

Thirdly, 1200 simulation experiments that were designed and analysed in this research are reflective of typical production scenarios in house building but are not comprehensive of every problem that could happen in construction sites. This should be taken into consideration that every construction project has its unique production environment and stochastic variables to be modelled.

7. Conclusions

Prior work has documented the effectiveness of rate-driven construction in improving tangible performance measures in construction projects (Choi and Minchin Jr 2006). Rate-driven construction, however, does not consider due date integrity explicitly and an additional control measure in form of a capacity buffer is required. Existing research in the construction literature in order to investigate tangible effects of capacity buffers on production metrics and the optimal size for such buffers is sparse. To bridge this gap, this study tested a user-friendly framework for finding the optimal size for capacity buffer that maximises the workflow stability and minimises the probability of late completions. Towards this aim, production data of two Australian construction companies were collected and analysed. Gross production capacity of the network was computed by using time series analysis. Then, cost and capacity optimizations were conducted to find the optimal size of the capacity buffer. Following this, results of mathematical modelling were linked to a discrete-event simulation engine and different real-life production scenarios caused by varying stochastic variables of construction production were analysed.

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The robustness of the framework in order to improve workflow stability through establishing a capacity buffer was tested. Findings show that an optimal-sized buffer can help construction systems in maintaining a synchronised production in which output and demand are coordinated. These findings extend those of Nasir, Haas et al. (2012) and Ballard (2000), confirming the positive impact of reducing and buffering variability on improving the productivity in construction. In addition, the results show that setting the optimal capacity buffer requires making trade-offs between lost revenue opportunity caused by big buffers and late completion costs caused by small capacity buffers.

8. Research contributions and opportunities for extensions

This work contributes to the body of knowledge by developing a deeper understanding of the role of capacity buffers in improving workflow stability in the construction production. The proposed framework avoids oversized buffers since they are wasteful, hinder performance, and disrupt the workflow. Furthermore, using the framework does not create undersized buffers as they increase the risk of late completions and a poor service level. The user-friendly framework is intended to assist builders in finding the most cost-effective way to operate their network of trade contractors. The authors are currently working on more sophisticated optimization models that consider more stochastic variables in real-world construction settings.

The framework was used at the project level in order to compute the gross production capacity and then the optimal capacity buffer for the entire construction network. It is recommended that the framework is also used at the specialty contractor level so as to compute the optimal capacity buffer for each single trade.

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Figure Captions

Fig.1. Framework for improving the workflow stability using an optimised capacity buffer

Fig.2. Process of data collection and analysis in the current research

Fig.3. Gross production capacity of the trade contractor network (house/month)

Fig. 4. Production curves of construction networks, (a) Standard deviation of time between completions (Workflow stabilit and (b) Capacity buffer (92% service level)

Fig. 5. Upward trend in the size of the capacity buffer resulted by increasing the standard deviation of time between completions

Fig. 6. Histogram of collected data on inter-arrival times

Fig. 7. Optimal size of the capacity buffer in simulation experiments (enforcing a growing service level)

Fig. 8. Simulation results on Target house completion and size of the capacity buffer

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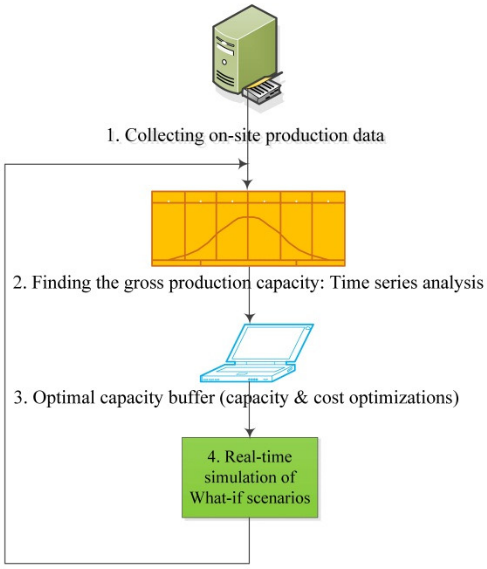

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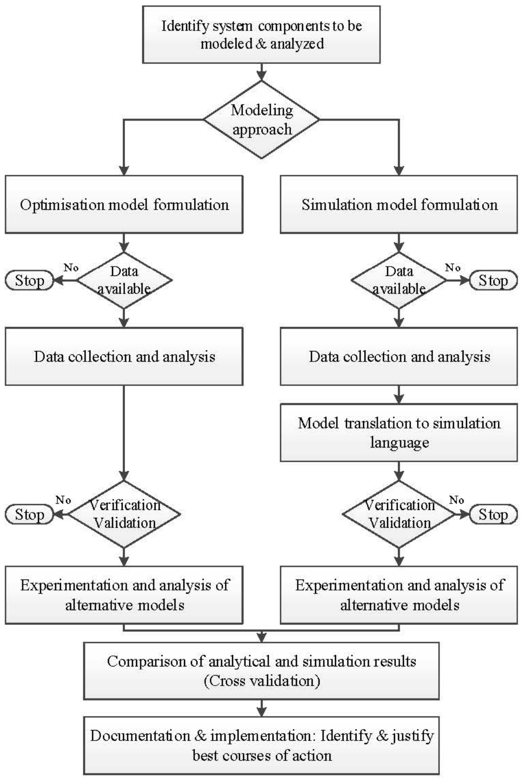

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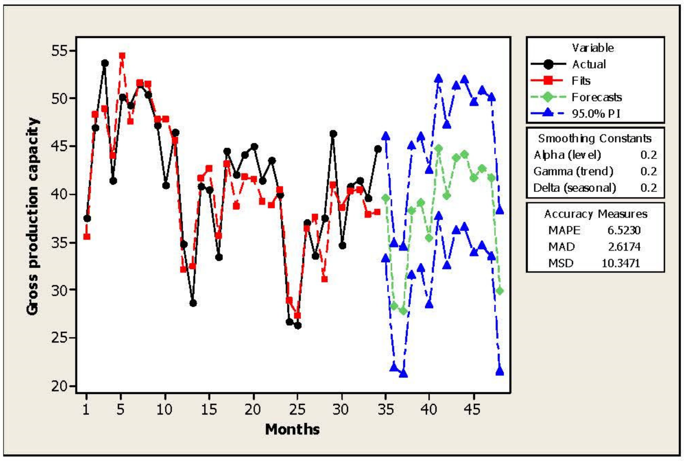

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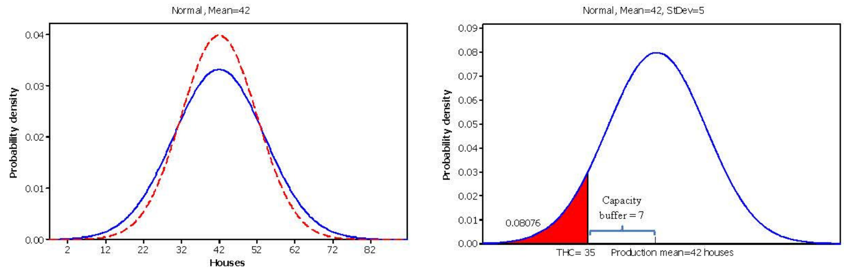

Fig. 4a. *Standard deviation of time between completions (Workflow stability)* ***Fig. 4b.****Capacity buffer (92% service level)*

Fig. 4. Production curves of construction networks

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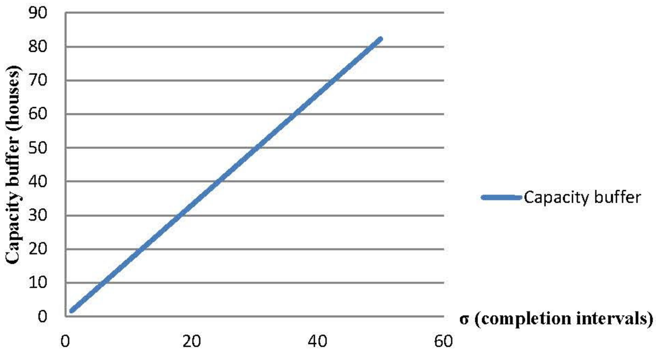

Fig. 5. Upward trend in the size of the capacity buffer resulted by increasing the standard deviation of time between completions

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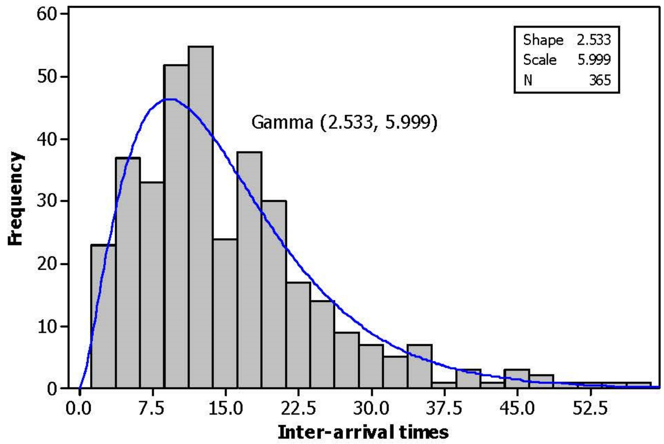

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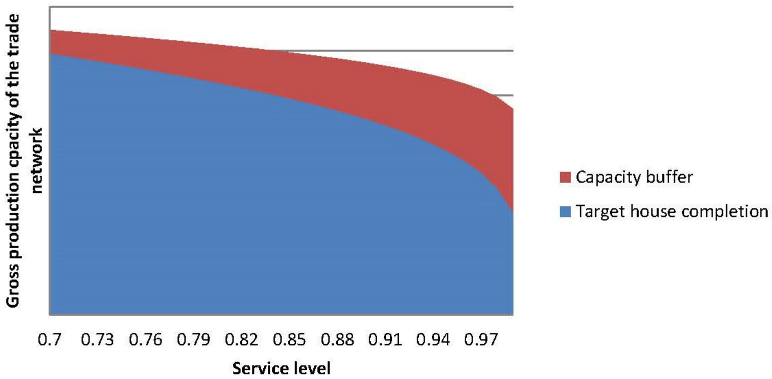

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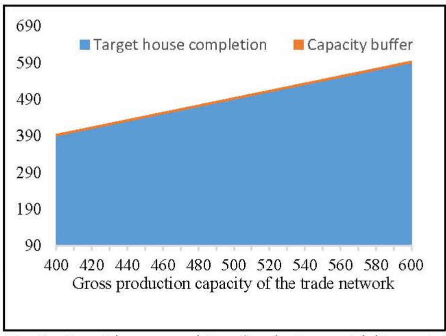

Fig. 8a. Target house completion (production variability controlled)

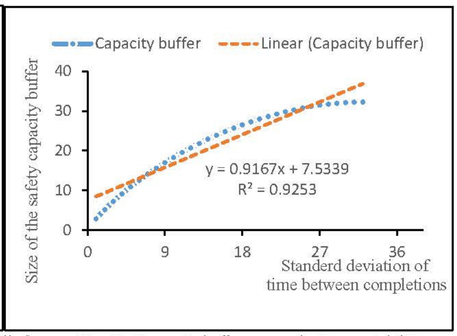

Fig. 8b. Capacity buffer vs. production variability

Fig. 8. Simulation results on Target house completion and size of the capacity buffer

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Table 1. Three quantitative measures for evaluating the accuracy of gross capacity forecasting

Accuracy measure	Moving average	Single exponential smoothing	Double exponential smoothing	Winters method
MAPE	14.85	13.40	13.76	6.52
MAD	5.01	5.05	5.17	2.62
MSD	45.49	38.53	41.97	10.35

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Table 2. Capacity buffer in 18 production scenarios with different service levels

σ	1									2								
μ	9			10			11			9			10			11		
$SL\%$	85	90	95	85	90	95	85	90	95	85	90	95	85	90	95	85	90	95
THC	8.0	7.6	7.4	8.9	8.7	8.4	10.0	9.7	9.5	6.9	6.4	5.6	7.9	7.5	6.7	9.0	8.4	7.7

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Table 3. Capacity buffer in 12 production scenarios with different late completion costs

C_{LC}	350						400					
σ	1			2			1			2		
μ	9	10	11	9	10	11	9	10	11	9	10	11
THC	7.6	8.7	9.6	7.4	8.5	9.4	7.5	8.4	9.5	7.1	8.0	9.1